NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT 11

EFFECT OF CONTROL DEVICES ON TRAFFIC OPERATIONS

INTERIM REPORT

HIGHWAY RESEARCH BOARD NATIONAL ACADEMY OF SCIENCES - NATIONAL RESEARCH COUNCIL

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INTERIM REPORT

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CHICAGO, ILLINOIS

HIGHWAY RESEARCH BOARD OF THE DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH
NATIONAL ACADEMY OF SCIENCES - NATIONAL RESEARCH COUNCIL 1964

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by Highway Planning and Research funds from participating member states of the Association and it receives the full cooperation and support of the Bureau of Public Roads, United States Department of Commerce.

The Highway Research Board of the National Academy of Sciences-National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway departments and by committees of AASHO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Highway Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

This report is one of a series of reports issued from a continuing research program conducted under a three-way agreement entered into in June 1962 by and among the National Academy of Sciences-National Research Council, the American Association of State Highway Officials, and the U. S. Bureau of Public Roads. Individual fiscal agreements are executed annually by the Academy-Research Council, the Bureau of Public Roads, and participating state highway departments, members of the American Association of State Highway Officials.

This report was prepared by the contracting research agency. It has been reviewed by the appropriate Advisory Panel for clarity, documentation, and fulfillment of the contract. It has been accepted by the Highway Research Board and published in the interest of an effectual dissemination of findings and their application in the formulation of policies, procedures, and practices in the subject problem area.

The opinions and conclusions expressed or implied in these reports are those of the research agencies that performed the research. They are not necessarily those of the Highway Research Board, the National Academy of Sciences, the Bureau of Public Roads, the American Association of State Highway Officials, nor of the individual states participating in the Program.

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FOREWORD

By Staff
Highway Research Board

This interim report will be of particular interest to traffic engineers and to highway administrators responsible for traffic operations. The research reported here is concerned with the effects of STOP and YIELD signs on traffic operation and safety. The report will contribute substantially to existing knowledge and understanding of the proper application of STOP and YIELD signs and the results to be expected from their use. The research agency studied present practices in the control of intersections with such signs. Through controlled research, the agency has filled several gaps in the knowledge of this area. Detailed procedures for further studies, including both data collection and analyses, are described. Also suggested are ways to expand the studies from individual intersections to adjacent intersections and complete street systems.

Little research had been conducted in the past to determine the anticipated effects on capacity, operations, and safety from the use of the STOP and YIELD signs in a traffic network. As a result, only very general policy statements could be proposed for warrants and installation of STOP and YIELD signs.

This interim research report describes the parameters involved in a set of pilot studies conducted in the Chicago area to determine the effects of STOP- and YIELD-sign installations. They include speed, volume, gap and lag acceptance, travel time and delay, safety, headway distribution, route choice, and driver actions. The methods of data collection included time-lapse photography, enoscope speed studies, manual counts, driver questionnaires, and travel studies conducted with Greenshield's drivometer.

The pilot studies deal with the evaluation of the parameters for individual intersections, the measurable effects from control on adjacent intersections, and travel route pattern changes that developed from the new installation or change in type of traffic control device. Statistical analyses of the data were made. The results were also compared with findings from research conducted by others.

A section of the report is devoted to a review of traffic simulation on electronic computers for at-grade intersections. From the review, recommendations are made for further study of a number of desirable components of a simulation model which would be used in a later stage of research.

The research conducted during the first phase of this contract was to develop techniques and procedures through pilot studies. It was further reasoned that some preliminary relationships would arise from the results of the pilot studies. The research agency will proceed to conduct studies to evaluate STOP- and YIELD-sign controls. These studies, carried out from their offices in several regions, will be

designed to gather data on a set of parameters which were selected on the basis of the first-phase work. Emphasis will be placed on obtaining basic operational characteristics which are universally applicable. It is anticipated that the research will result in recommended criteria for the installation of these traffic control devices. It is also anticipated that the findings will provide the traffic engineer and the highway administrator with an understanding of the expected operational advantages and deficiencies of these devices in the traffic network.

Although the STOP and YIELD signs are but two of many traffic control devices which may be studied, they are of particular interest because of their widespread use, low initial cost, and ease of installation. Documenting the effects of these in the traffic system will provide an important contribution to the field of traffic engineering.

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ACKNOWLEDGMENTS

A project of this type required the cooperation of a number of people and agencies in order that it be carried out in an effective manner. Their contribution is acknowledged herein, with appreciation for their efforts.

This research was conducted under the guidance of Messrs. Jack E. Leisch and Walter A. Barry, Jr. Engineers on the project were Messrs. Ronald C. Pfefer, Charles E. De Leuw, Jr., and Emmanuel F. Klaesi. Others assisting on the project field work and analyses included Mrs. Gertrude Muranyi and Messrs. Gary Long, Harold Beardslee and Joel Leisch. Dr. Bruce D. Greenshields, of the University of Michigan, loaned the instrumented vehicle to the project and provided consulting advice on the use and application of the drivometer as it related to the route study. Dr. John E. Baerwald, of the University of Illinois, provided consulting advice during the preparation of the route study and participated in the attainment of arrangements for control changes at the Oak Park site.

Various city and village officials in Illinois aided in the choice of sites and cooperated in the studies which followed. Mr. Glen Sunde, Mr. Max Whiteman and the Village Board of Oak Park arranged for and carried out the temporary control changes along Augusta Boulevard during the route study. The progressive attitude of these officials overcame certain isolated objections to these changes, thus permitting the study to proceed. Messrs. John Scapin and Edward Whiteside, of the Village of Wilmette, recognized the usefulness of the project and permitted and supervised the control changes at Fifth Street and Linden Avenue. Messrs. Robert Meyer and Lester Maloney, of the Village of La Grange and La Grange Park, respectively, cooperated fully during the studies performed there. Data relating to the location of YIELD and STOP controls in Chicago and Cook County, and intersections where control changes were planned, were supplied by Mr. Richard Fencl and Mr. Henry Peck of the City of Chicago, and Mr. Leo Wilkie of Cook County. Mr. Zeto Faulkner, of Evanston, provided information during preliminary efforts to locate suitable study sites. The police departments in each area studied extended every courtesy in supplying the necessary accident data.

Engineers from the State of Illinois Department of Highways who aided include Messrs. Michael Hartigan, George Hagenauer, T. D'Arcy Sullivan, Gerhart King, and William Stebbins, who were instrumental in supplying volume counts throughout the area during the preliminary study, in addition to allowing the use of state cameras and projectors, and providing the supplementary signs used in Oak Park.

Additional projectors were rented from Northwestern University through the cooperation of Dr. Donald S. Berry and Mr. Richard Worrall.

Dr. Thomas Rockwell and Mr. Richard Snyder, of Ohio State University, were consulted on various aspects of an instrumented vehicle and its usefulness as applied to a route study, in addition to reviewing psychological factors that might be worthy of study.

The foregoing acknowledgments are of the major contributors. Gratitude is also expressed to the many others who were involved, including the authors and libraries that supplied data and publications for review.

EFFECT OF CONTROL DEVICES ON TRAFFIC OPERATIONS

INTERIM REPORT

SUMMARY

The increasing need for more efficient use of urban streets led to the creation of this project, whose purpose is to study the effect of specified control devices on operation of individual intersections and on operation within a surrounding street system. The ultimate goal is to gain information usable in developing warrants to guide engineers in the placement of these controls. The first stage of the study, reported here, is a pilot investigation to determine efficient methods of study and to derive some preliminary relationships concerning the operation of intersections with YIELD control and two-way STOP control, and the effects of these controls on a system of streets.

The study is divided into two parts—the effect of STOP and YIELD control on (a) individual and adjacent intersection operation, and (b) operation along a traffic corridor.

The study of individual intersection operation is based on the theory that because the driver need not stop at a YIELD sign in every instance, he has some advantages over similar situations with STOP control. The driver approaching a YIELD sign can adjust his speed so as to arrive and proceed through the intersection without stopping. If he does not stop, he can arrive at the intersection sooner and, by passing the control sign at some initial speed greater than zero, complete his maneuver quicker than if he had stopped.

Five intersections in suburbs in the Chicago metropolitan area were chosen for study. In two cases, where controls were changed as part of the study, before-and-after studies were performed. Each of the intersections is located in an urban street environment. The traffic on either the major or the minor street does not exceed a two-way volume of about 400 vph. The speed limits on the study streets are about 25 or 30 mph. Items (parameters) chosen to describe operation at an intersection included volume of traffic, vehicular speeds and deceleration-acceleration characteristics, delay to minor-street vehicles, spacing of vehicles as they arrive and depart from the intersection, size of the opening between vehicles on the major street that minor-street vehicles move through (or refuse to go through), and accident and driver obedience characteristics. Field measurements of these parameters were made through the use of time-lapse photography, stopwatches and mirror devices (enoscopes), and manual volume counts.

The study of operation along a corridor is based on the theory that drivers have their own personal criteria for choosing the path they follow, and that the placement of traffic control devices (specifically STOP signs) has a major effect on these items. The criteria suggested as being important include overall travel time, distance traveled, stopped-time delay, driver actions (steering wheel, brake and accelerator movement), and vehicle dynamics (speed and direction changes).

A corridor consisting of two parallel arterial streets 0.3 miles apart and 1.5 miles long was chosen for investigation. Traffic volume along each of the two major streets running the length of the corridor is in the range of 400 to 700 vph during the peak period.

Field measurements were accomplished with (a) an instrumented vehicle (the Greenshield drivometer), (b) a driver mail-back questionnaire, and (c) manual volume counts.

The study also included review of a number of computer simulation projects which have been used to simulate the operation of an intersection. This was done in order to evaluate the usefulness of this technique for this project, and to develop guidelines for conducting such a study if it should be warranted.

Minor-street drivers generally will move through openings of 20 sec or greater on the major street 100 percent of the time. For openings below this size, there is a greater probability that a minor-street driver will accept the initial opening (lag) of a given size in the major-street traffic stream under YIELD-sign control than under STOP-sign control. Having rejected a lag, however, there is less probability that the driver at a YIELD sign will accept the immediately following opening (gap), than if he were at a STOP sign. This overall characteristic results in a smaller delay per vehicle under YIELD control than under STOP control, at the volumes studied. At one intersection the total delay was found to be about 2 to 3 sec less per minor-street vehicle with the YIELD-sign than with STOP-sign control in conjunction with major-street volumes approaching 300 vph. A study of a number of intersections showed almost no difference in stopped-time delay with either control in conjunction with a major-street flow rate of 100 to 200 vph. At rates of flow on the major street approaching 400 vph, the stopped-time delay per minor-street vehicle under STOP control was found to be 5 to 6 sec greater than under YIELD control.

The gap and lag acceptance characteristics of drivers are complex phenomena which are affected by a number of factors, such as differences occurring between lag acceptance and gap acceptance, traffic volume on the major street, speed of traffic on the major street, character of the major street relative to the minor street, sight distance available to minor-street drivers, and time of day.

The type of control at one intersection was found to have little effect on the speed of approach at the next intersection. The deceleration characteristics of vehicles approaching either control did not differ to within about 100 ft of the control, but sight distance restrictions were found to play an important part here.

In general, at the volumes studied the vehicles arrived in a random manner which could be closely predicted by the mathematical Poisson distribution; the presence of a YIELD or STOP sign did not seem to alter this randomness.

YIELD signs were found to decrease overall accident experience at previously uncontrolled intersections. No similar information was available to compare STOP and YIELD control. When the YIELD sign is placed against the street having the heavier of the two flows, there is an increase in disobedience over the condition with proper application of the control device. A voluntary full stop is not a popular practice, regardless of the control studied.

Upgrading of the priority along a length of roadway, by removing STOP signs, can increase the quality of flow along the route by decreasing delay, speed changes, and running time. This change causes an attraction to the upgraded route relative to the alternates available. However, the streets intersecting the improved roadway can be adversely affected.

Computer simulation to study intersection operation with various control devices would be a useful project. In order to conduct such a study the immediate need is for field measurements of traffic characteristics which can be programmed into the model to develop effective simulation. Some of the characteristics are indicated in a preliminary form in this report.

CHAPTER ONE

INTRODUCTION

NATURE OF THE PROBLEM

The growth in ownership and use of motor vehicles since 1946, and the prospect of even greater increases in the future, have alerted public officials to the problem of providing adequate facilities for the safe and expeditious movement of traffic. Governments at all levels are spending large sums for transportation studies, in anticipation of the need to spend much greater amounts for future improvements.

The problems in cities and metropolitan areas have already reached major proportions. More than 45 percent of all vehicle travel in the United States in 1961 was on urban streets which comprise only 12½ percent of the total highway mileage (7.03). * Each year, proportionately more travel originates in suburban areas; as of 1960, about one-half of the people in urban areas lived in suburban communities surrounding central cities (7.04).

Inasmuch as urban transportation systems are planned with emphasis on auto travel, it becomes increasingly important to insure the optimum operation of the system. Therefore, detailed study should be given each element to gain complete understanding of its operation and its relation to each of the other elements.

One very important component is the control system for at-grade intersections. The major effect on surface street operation occurs at these points.

Every driver would like to proceed as he pleases through the street network from his origin to his destination. Because his path crosses that of other vehicles at intersections in the system, however, it is desirable to minimize the chances that the potential intersection of vehicle paths will result in collisions.

The paths of two vehicles can be separated by either time or space. When a few vehicles are distributed over a relatively large number of streets, the separation in time, due to low probability of interference, usually obviates any need to control the intersection points. When street use becomes more intense, however, the probability of time separation by chance becomes smaller. When the severity of the problem justifies it, vehicles can either be separated at intersection points by space (grade separation), or rules can be established to force a time separation. The rules are applied through traffic control devices, starting with the give-way-to-the-right rule and proceeding over a wide range of controls from YIELD signs to traffic signals.

The degree of control should increase with increasing probability that time separation will not occur by mere chance. Therefore, the rules change from those requiring restriction of one or two streams (YIELD and two-way STOP) to those requiring restriction of all intersecting streams (four-way STOP and signal control). In many cases, restrictions on all streams are necessary because control of just one or two would put such burdens on the controlled flow as to be intolerable.

Drivers do not always use controls as intended. Questions also arise as to whether a positive control is better than one which is less positive. Questions are asked such as: "Is a four-way STOP safer than a two-way STOP?" or "Is there really any difference between the YIELD sign and the STOP sign?"

It is important that the engineer know which control is best for a given intersection condition. However, only meager information is available concerning controls below the level of traffic signals. Therefore, the overall objective of this study, as set forth in the Project Statement, is "to better identify the effect of specified traffic regulatory devices on intersection capacity and operations, and the system of traffic facilities." Once this type of knowledge has been gained, it will be relatively easy to develop sound criteria for use in the application of these devices.

INITIAL OBJECTIVES

It was decided, after detailed consideration of the purpose of the project, that the first stage should consist of a series of pilot studies on unsignalized intersections, with particular emphasis on analyzing YIELD and two-way STOP controls. These studies would develop information for organizing and conducting a second-stage study designed to produce an integrated theory on the effect of unsignalized controls on operation at intersections and in street systems.

Rather than placing emphasis on obtaining conclusive results on intersection operation, therefore, the policy was to test a number of methods of measurement and a variety of approaches, each of which seemed useful. The objective of these pilot studies was to obtain valuable information as to the most accurate and efficient methods of measurement, as well as to determine the parameters best suited to the purposes of the project. This experience is to be applied to detailed research during the second stage.

It was also reasoned that some indicative results would be obtained as a major by-product of the first-stage work and that they could be used to form a set of preliminary relationships. Obtaining such relationships would be useful not only for further testing on this project during the second stage, but also for investigation by other interested researchers.

* Numbers in parentheses refer to corresponding reference numbers in Appendix C.

CHAPTER TWO

GENERAL THEORY

UNSIGNALIZED INTERSECTIONS

The operational rules at unsignalized intersections require more interpretation on the part of the driver and more activity, skill and alertness than at signalized intersections. In order to study the control of unsignalized intersections, an attempt must be made to consider fully the driver behavior aspects of the operation since there is more interplay between drivers than at signalized intersections. Another important characteristic of unsignalized intersections is that the rate and instant of arrival of vehicles is of major importance, because it is vehicle presence in the crossing stream that determines what the driver in an approaching vehicle does.

YIELD AND TWO-WAY STOP CONTROL

Of particular interest during this stage of research is the comparison of YIELD control and the two-way STOP control (hereinafter referred to as STOP control).

The background and development of the YIELD sign and the STOP sign has been recorded in a number of places (1.02, 1.13 to 1.16, 7.07, 7.16). Both YIELD and STOP control have been in use long enough that the existence of such controls and the general type of signs employed is well known and does not warrant discussion here. Because the standardization of the general shape and message on the YIELD sign is of recent date, there are still some minor variations in the type of sign installed in different communities. This is discussed in Appendix A, which includes sketches of the several types of YIELD signs involved in this study.

In studying the differences in effect on traffic behavior between YIELD and STOP signs, it is pertinent to refer to the Manual of Uniform Traffic Control Devices (7.07), which delineates the general relationship between the two controls, as follows:

> *Section IB-5*
>
> Many of the conditions covered by the STOP sign warrants above can be dealt with by the YIELD signs with less inconvenience to the public. Use of the YIELD sign should be considered where sight distances are adequate and where a full stop at all times is not necessary.
>
> *Section IB-8*
>
> Generally the YIELD sign serves a purpose similar to that of the STOP sign, in that it assigns right-of-way to traffic on certain approaches to an intersection. Since it does not require all vehicles to stop, it should not be used where visibility limitations or prevailing high speeds or volumes of traffic make a full stop necessary for safety.

The warrants given for the YIELD and STOP signs generally deal with specific conditions for application. No specific volume or delay warrants are given. Accident criteria are given only in a very general manner.

Further understanding of the differentiation between YIELD and STOP control can be gained by review of the legal requirements of the driver at each control.

Illinois law requires that "... driver of a vehicle shall ... stop in obedience to a STOP sign as required herein at an intersection where a STOP sign is erected at one or more entrances thereto ... and shall proceed cautiously, yielding to vehicles not so obliged to stop which are within the intersection or approaching so closely as to constitute an immediate hazard, but then may proceed." For YIELD control, the law states: "The driver of a vehicle in obedience to a YIELD RIGHT-OF-WAY sign shall reduce speed of his vehicle to not more than 20 miles per hour and shall yield the right-of-way to other vehicles which have entered the intersecting highway either from the right or left or which are approaching so closely on said intersecting highway as to constitute an immediate hazard; but said driver having so yielded may proceed at such time as a safe interval occurs." A positive control is put on the driver at a YIELD sign by a further provision: "If a driver is involved in a collision at an intersection or interferes with the movement of other vehicles after driving past a YIELD RIGHT-OF-WAY sign, such collision or interference shall be deemed *prima facie* evidence of the driver's failure to yield right-of-way" (7.06). The provisions referred to here are very similar to those found in the Uniform Vehicle Code (7.15).

It is apparent from the legal requirements that the only operational difference between YIELD and STOP control is that at the former the driver has the choice of being in motion while moving past the control, whereas he must come to a full stop under STOP control.

GAP AND LAG ACCEPTANCE AND THE TIME ADVANTAGE

A lag at an intersection control may be defined as the time interval between the arrival of the minor-street vehicle opposite the control, and the arrival thereafter of the first major-street vehicle at the midpoint of the intersection. A gap at an intersection is defined as each time spacing formed by successive crossings of the midpoint line by major-street vehicles, regardless of direction of travel. If the minor-street vehicle moves through the intersection before the arrival of the first major-street vehicle, the driver of the minor-street vehicle is said to "accept" the lag. If he remains until after the first vehicle passes, he has "rejected" the lag. Having rejected the lag, he is then confronted with the gaps between successive vehicles. Each gap that he fails to move into is also said to be rejected. The gap through which the driver finally proceeds is, of course, said to be accepted.

At the YIELD or STOP sign, it is the ability of the minor-street vehicles to accept lags or gaps, without interference with the major-street traffic, which directly affects the capacity and operation of the intersection. Therefore, it

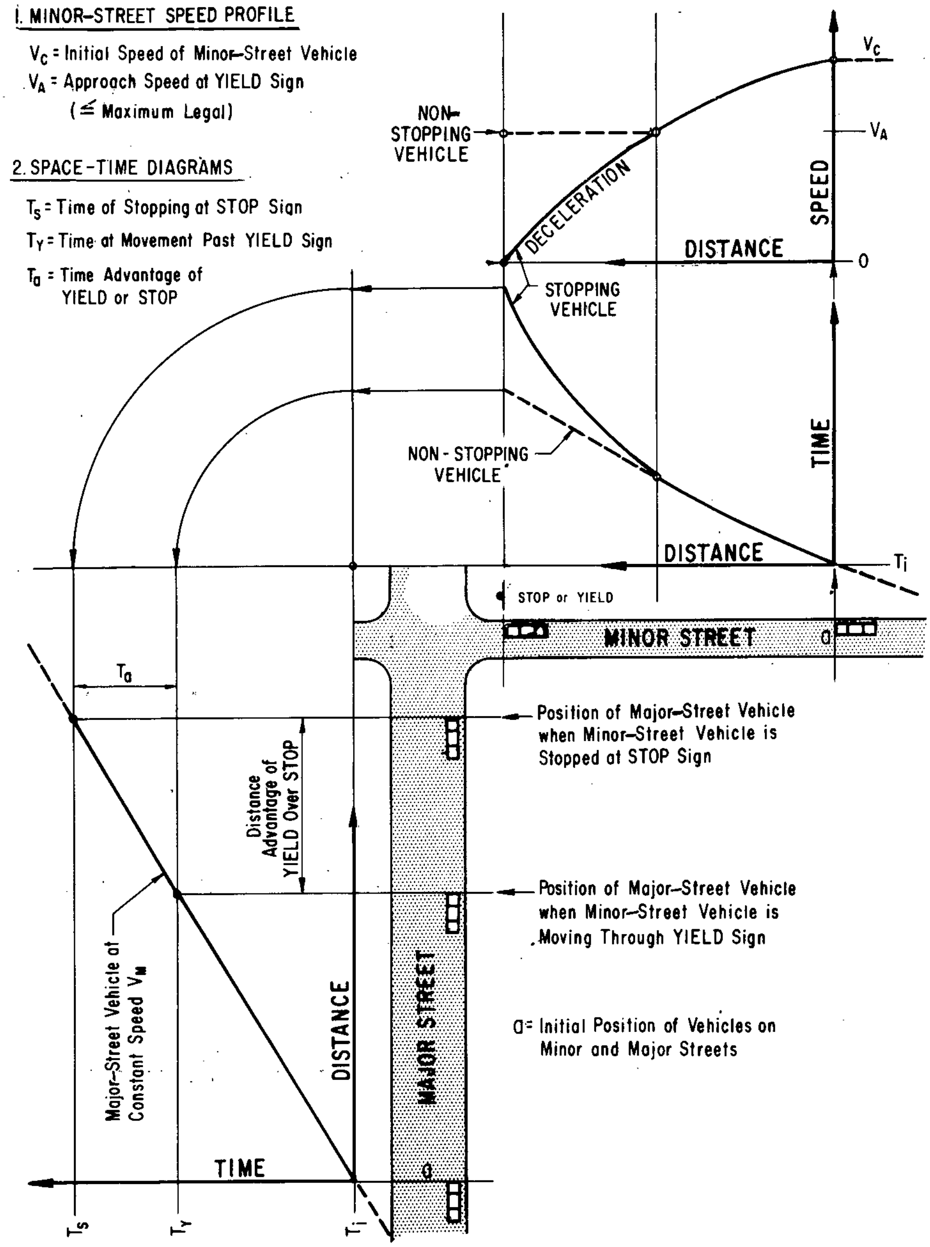


Figure 1. Vehicle operation on approach with YIELD *or* STOP *control.*

is of primary interest to determine what the gap and lag acceptance characteristics are and to identify the factors which affect them.

As previously stated, the legal definition of the YIELD maneuver indicates that the major difference is that the driver can be in motion at the control. This means that a lag may be accepted while in motion. It can also include gaps if the case is considered where the driver times his arrival to be just an instant prior to the passing of the lead major-street vehicle, and then moves immediately behind him to accept the following gap. This is not likely to occur often. It would be of interest, therefore, to analyze how this difference affects gap and lag acceptance.

Figures 1 and 2 show two types of time advantages that the driver has when approaching a YIELD control as compared to STOP control. The first has to do with vehicles approaching on the minor street, and is the time advantage gained on the approach because the driver need not decelerate to a stop if he is not required to yield. The second has to do with vehicles entering the intersection from the minor street, and is the advantage gained due to reduced time in the collision zone within the intersection because the driver can be in motion at or below some maximum legal approach speed at the YIELD sign when beginning his intersection maneuver.

Figure 1 shows an example of the first type of time

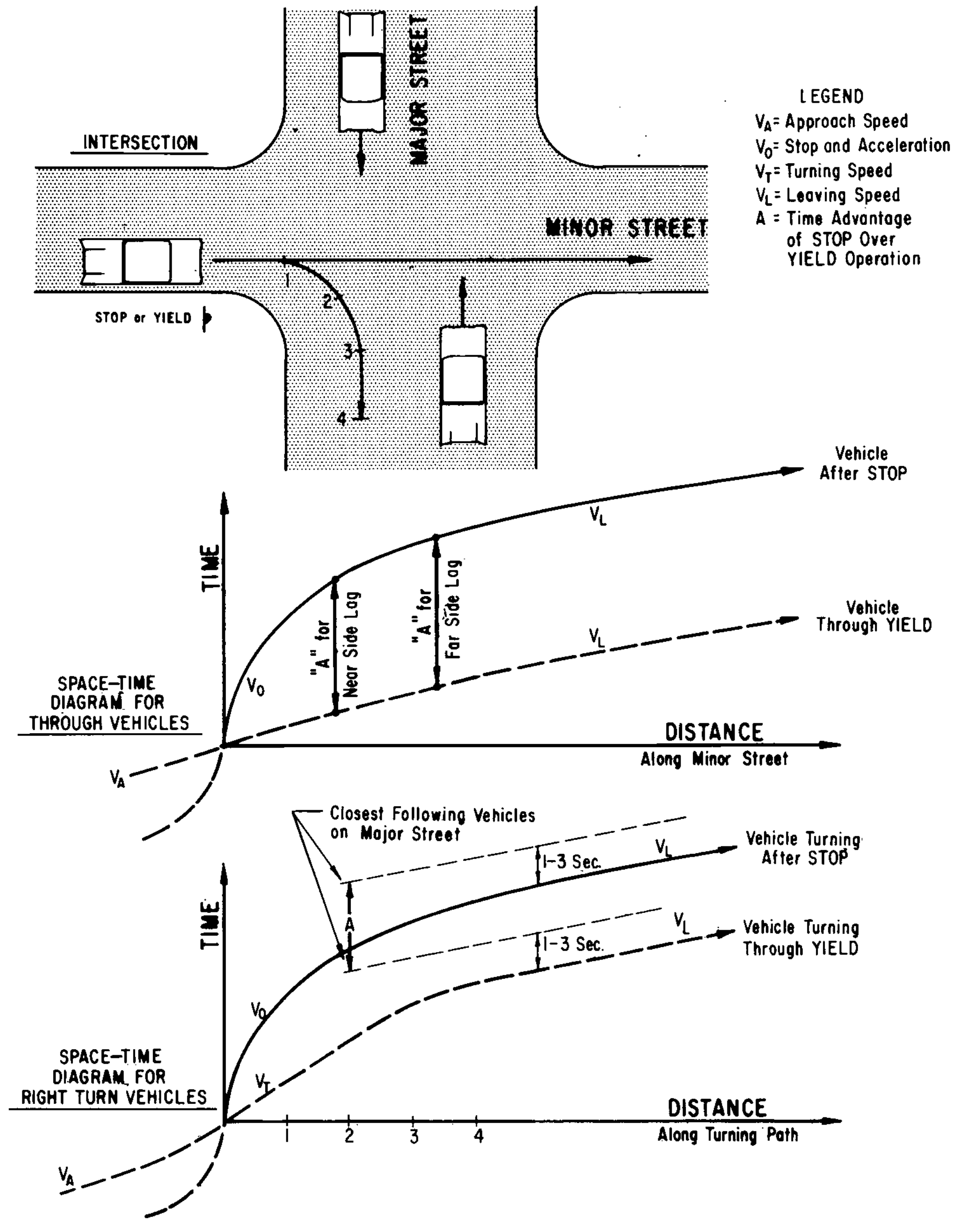


Figure 2. Vehicle operation within intersection with YIELD *or* STOP *control.*

advantage. The driver approaching the YIELD sign, having observed that no vehicle is approaching to which he must yield, can continue to approach the intersection at a speed at or below the legal maximum for the YIELD control. Therefore, he will arrive sooner than the driver who is required to decelerate to a stop. The time advantage of YIELD control will vary with the position of the major-street vehicles. Two cases arise. For the purpose of discussion, assume the side-street driver will accept a lag equal to or greater than L seconds and that the time advantage between arrival at a STOP and YIELD sign is T_a seconds (see Fig. 1).

Case I—A lag of size greater than zero and less than L seconds is formed between the major-street vehicle and the vehicle at a STOP sign. In this case the STOP-controlled driver will reject the lag. For the YIELD sign, however, the driver could estimate the time advantage T_a. If T_a plus the lag size that occurred for the STOP-controlled vehicle is greater than or equal to L, the minor-street driver could continue and arrive at the YIELD sign with a lag at or above L. If T_a plus the original lag is less than L, however, the driver would realize he must yield and, according to the assumptions used, would decelerate to a stop just as for a STOP sign, but he should be delayed no longer than at a STOP control.

Case II—The major-street vehicle forms a lag with the vehicle at a STOP sign greater than L. For this

condition the time advantage at a YIELD sign is of no significance since the driver will accept the lag at either control.

This discussion has shown that delay for each vehicle at a YIELD-controlled intersection operating under these assumptions is equal to or less than at a similar STOP-controlled intersection. Therefore, the average delay per vehicle is likely to be less at the YIELD-controlled intersection. The effect of the second type of time advantage, however, has not yet been discussed.

Figure 2 shows the time advantage to vehicles entering the intersection from the minor street at a YIELD sign, when not having to stop. Separate cases are shown for turning and non-turning vehicles. The examples shown indicate that the initial velocity of a non-stopping vehicle reduces the time that the vehicle is in the collision zone from the corresponding time for a stopped vehicle.

Because the driver confronted with a YIELD control can be in motion at the time he is opposite the control, he has the advantage of initial speed (greater than zero) when entering the intersection. This initial speed allows him to complete his intersection maneuver in a shorter time than the vehicle starting from a stopped condition. Consider the following example for the through vehicle, using average values.

Let:
Minor-street approach speed to a YIELD control = 15 mph or 22 ft per sec.
Acceleration across intersection from stopped position = 7 ft per sec per sec.
Width of the major street = 44 ft.
Offset of the control from the curb line = 12 ft.
Acceleration across intersection from approach speed = 4 ft per sec per sec.
Required clearance of crossing vehicles = 2 ft.

Then:
Time to complete maneuver from STOP sign = 3.2 sec.
Time to complete maneuver from YIELD sign (moving at approach speed) = 1.5 sec.
Decrease in time to complete maneuver = 1.7 sec.

This decreased maneuver time can be thought of as an increase of the lags by 1.7 sec, which can greatly affect probability of acceptance of lags in the critical range where the driver is on the borderline between acceptance or rejection. This reasoning could apply equally to the turning maneuver as shown in Figure 2.

This discussion has shown that the added choice available to the driver at a YIELD sign can affect his acceptance characteristics favorably, and aid in cutting his delay. It seems likely that the extent of the benefit will vary with intersection and traffic conditions.

EFFECT OF VARIATION OF PHYSICAL FEATURES AND TRAFFIC CONDITIONS

Sight Distance

With clear view of the intersection and its approaches, the driver on the minor street is able to process information at an early point in time while approaching a YIELD sign. This allows him more opportunity to judge whether or not his time advantage is enough for him to continue without yielding. While approaching the STOP sign, the driver can consider what his maneuver will be after stopping, so that he can get started immediately after completing the stop without requiring any further time to make a decision. As sight distance is reduced, however, the time available for these processes is also reduced and the probability of making a wrong decision increases.

For any given intersection there will be a point of sight restriction below which some drivers will slow to gain more time for decision. As the restriction becomes more severe, it will no longer be possible for a driver to see a vehicle on the cross street in time to stop safely unless he reduces his speed below that which he uses between intersections. The speed above which it is unsafe to proceed is called the "safe approach speed" (SAS). Thus, as sight distance is reduced, the SAS becomes lower.

Considering this, it is possible to theorize several effects of sight distance restriction on operation at YIELD- and STOP-controlled intersections. First, the flexibility the driver enjoys while approaching a YIELD sign is reduced by sight restrictions. Such restrictions move closer to the intersection point at which the driver can fully estimate his time advantage, thereby reducing the time available for adjustment of his speed to time his arrival correctly. For both YIELD and STOP control, a reduction of the amount of time available to determine the correct maneuver at the intersection should tend to decrease the probability of acceptance of smaller lags. At a YIELD control, when SAS falls below the maximum approach speed to the YIELD sign which is allowed by law (if such a law exists), safety, rather than legal considerations, will begin to influence the driver's actions. At this point, any reduction in SAS diminishes the time advantages of the YIELD control further, until the operation approaches that of a STOP sign with respect to time advantages and delay.

Traffic Volume

The variation in traffic volume on the major street directly affects the size and number of headways in a stream. As this happens, the probability increases that a minor-street vehicle will have to yield at a YIELD sign. As the volumes on the major street rise, therefore, the operation at a YIELD sign will approach that of a STOP sign.

Furthermore, it has been pointed out that the driver must process a number of pieces of information while approaching the control. As volume increases, the amount and complexity of information requires longer processing time. Investigation of the effect of major-street volume on gap and lag acceptance should indicate whether there is equal effect on operations at YIELD- and STOP-controlled intersections. Variation in minor-street volume will directly affect delay at a given major-street volume, when volumes increase insufficiently to cause queuing. The increased delay to minor-street vehicles, due to queuing, will likely be greater with a given intersection volume condition at a STOP control than at a YIELD control because of the greater ability to move vehicles through the YIELD sign.

Speed

The effect of the speed of major-street vehicles on operation at YIELD and STOP controls is taken into consideration to some extent through measurement of gaps and lags in terms of time. Vehicle speed is also considered in measuring whether drivers approach within safe and legal limits. Another possible effect, not readily recognized, may be psychological: higher speed on the major street might make the minor-street driver more cautious because of the probable greater severity of any accidents that might occur.

Safety

Accident prevention is one major reason for installation of control devices. The philosophy is, "the more 'positive' the control, the safer the operation." Whether or not this is valid, it seems likely that STOP control presents the driver with a less dynamic situation than the YIELD control. At a STOP sign he can make an unhurried decision as to acceptance of a lag. STOP control also provides the major street with a more positive right-of-way because there is less likelihood of gross disobedience of a STOP sign than there is of a YIELD sign. There may be many rolling stops at a given STOP sign. Legally this may be important, but it is not likely to affect operation significantly if the "roll" is kept below 5 mph. On the other hand, the greater dependence on driver judgment at a YIELD control is likely to result in wider variation in driver behavior and, therefore, less orderly intersection operation.

SYSTEM CONSIDERATIONS AT INDIVIDUAL AND ADJACENT INTERSECTIONS

Headways

The headway distribution on an open highway is directly affected by volume level. A system of streets with any given control configuration, however, will cause redistribution of the vehicles as they flow through the system. Because distribution directly affects the capacity of an intersection, it would be of interest to study the manner in which controls in advance of an intersection affect arrival of headways at that intersection. If such an effect does occur, it is theoretically possible to have an infinite number of headway distributions with any major-street volume. Therefore, it would not be completely accurate to correlate delay, based on gap and lag acceptance, with major-street volume. It might be more realistic to relate it to the headway distribution.

Volumes and Speeds

Traffic assignments consider a system to consist of nodes connected by links. A street system can be thought of as intersection nodes connected by street links. Thus, it can be seen that the volume through an intersection is determined by the number of routes served by each leg (link) of the intersection and the attraction of each of those routes. Similarly, previous links and intersections have capacity limitations. If capacities of these street elements are exceeded, they act as metering devices, limiting the volume of flow through the intersection under consideration. In this manner, the surrounding system can affect volumes through an intersection and thus have a direct effect on the operation of that intersection.

The speed in a system is affected by such factors as the capacity of the system, traffic volume, signal timing, spacing of intersections, placement of controls with respect to protected routes, and speed limits. The effect of each is cumulative, and together they act as a combined speed determinant. The combination of these factors at locations prior to a particular intersection acts on the approaching vehicles so as to determine their speed through the intersection under consideration.

SYSTEM CONSIDERATIONS FOR ROUTE OPERATION

Traffic controls in a system are designed and placed in an attempt to obtain the maximum efficiency of operation from facilities serving a variety of travel desires. Certain routes of travel are usually preferred over others. Questions arise as to what criteria a driver uses in choosing a route and what part the controls in the system play in determination of route choice. Traffic assignment processes consider only time and distance as major criteria (together with toll charges, if any).

The psychological benefits of one route over another would also seem important. The more esthetic route might have added attraction. Certain irritants such as increased tension along a route, the number of stops that must be made regardless of overall delay, the smoothness of the pavement, and the amount of driving effort all seem to be likely criteria affecting a driver's choice. A driver will usually attempt to minimize distance, time, effort, tension, and exposure to accidents. As he considers the alternative routes available to him, he estimates these factors and chooses the alternative that best meets these criteria. It is apparent that controls along the route will affect these factors. It would be helpful to determine all the important criteria that the driver uses and what part each plays in the overall route choice. The next step would be to quantify the effect that intersection controls along the route have on each of these factors. This would allow prediction of the effect of a system of controls on route use and operation. It would be a valuable addition to the warrants used in selecting and placing traffic controls.

CHAPTER THREE

SCOPE AND METHOD OF STUDY

TYPE OF STUDY CONDUCTED

Study sites were chosen for the particular purpose of investigating STOP and YIELD control. Emphasis was given to YIELD controls, this being the area in which there seemed to be the greatest need for basic research. Field work on STOP controls was conducted at two-way and four-way STOP intersections. Studies were also made at a signalized intersection and at an uncontrolled intersection as yardsticks of operation under the upper and a lower limit of intersection control.

Data were collected to provide information in three basic areas:

1. The operation of an individual intersection and the effect of control condition on the operation.
2. The interaction which occurs between adjacent intersections and the effect that a control condition at one intersection has on the adjacent intersection.
3. The effect which a set of traffic controls has on operation along a traffic corridor and the route choice within the corridor.

Field studies were generally designed to obtain the data required in each of these areas simultaneously. In several cases a series of studies was made at the same location but under different control conditions. The use of before-and-after studies helped isolate the operational effects arising from the changes by holding most other factors constant.

PARAMETERS STUDIED

One of the major objectives of the first stage of research was to study the effectiveness of the various parameters of operation in describing the traffic characteristics of interest on this project. Each of the major parameters of intersection flow was investigated to determine its value for describing operation at an individual intersection, between adjacent intersections, and in a system of streets. The interdependency of the various parameters was also considered. The following is a summary of each parameter investigated in the study.

Speed

Characteristics which describe the level of intersection and system operation include speed profile, speed across an intersection, rate of change of speed, average speed, and maximum speed. Driver behavior may be affected by either the speed within the driver's stream or by the speed of the cross stream. Studies at individual intersections have shown correlation between speed and level of operation. Raff (2.33) found the "critical lag" to vary with major-street speed but indicated that it was not the only cause of variation. Matson *et al.* (7.08) shows a similar effect in a set of graphs which indicate acceptance of smaller headways by merging vehicles when there is a lower relative speed between the merging vehicle and the main-stream vehicle. Greenshields *et al.* (2.13) has correlated the effect of sight distance on approach speed characteristics at uncontrolled intersections. Kell (1.13) reports a study which showed higher speed and less deceleration on the approaches at two intersections where STOP control was replaced by YIELD control. Homburger (6.20) found that speed affects the point of decision of vehicles approaching uncontrolled intersections. Studies of travel in a street system have shown speed (as it affects time) to be important in route choice. Heimbach (9.08) has indicated that speed changes enroute have some correlation with shopping trip production.

Traffic Volume

Traffic volumes are recognized as an essential parameter for defining operational levels of flow. Volumes can affect measures such as headway distributions, speed, delay and accident rates. The distribution of volumes between minor and major streets of an intersection with a constant total volume has been shown to affect delay levels by Kell (5.11) and Lewis and Michael (5.14).

Gap and Lag Acceptance

Gap acceptance distributions are used to describe driver behavior at unsignalized intersections. The ability of a driver to move across or into a gap in traffic greatly influences the operating level of an intersection under a given set of conditions. Several attempts have been made to arrive at a single measure of acceptance: Greenshields *et al.* (2.13) measured a minimum acceptable time and Raff (2.33) measured the "critical lags." These values were found to vary by main-street speed, volume distribution and street width, but no significant correlation was obtained. The distribution of gap and lag acceptance has been studied by several investigators: Bissel (5.09) fitted a set of data to a theoretical distribution, Swerdloff (2.38) investigated peak *vs* off-peak characteristics, and Gagnon (2.12) attempted to determine the effect of following vehicles on acceptance. Blunden *et al.* (2.04) studied acceptance of stopped *vs* moving vehicles and also investigated the effect of commercial vehicles, main-street volume and type of headway on the acceptance distribution.

Travel Time and Delay

Delay is useful in describing the level of service at an intersection or in a system of streets. Also, it lends itself to economic analysis. The driver is annoyed by delay; he is constantly attempting to minimize it. It is useful to know what the major causes of delay are, and to what extent each contributes to the total. With such knowledge, the engineer can evaluate what the overall effect would be with removal of one of the causes of delay. Raff (2.33) developed an equation relating the percentage of cars

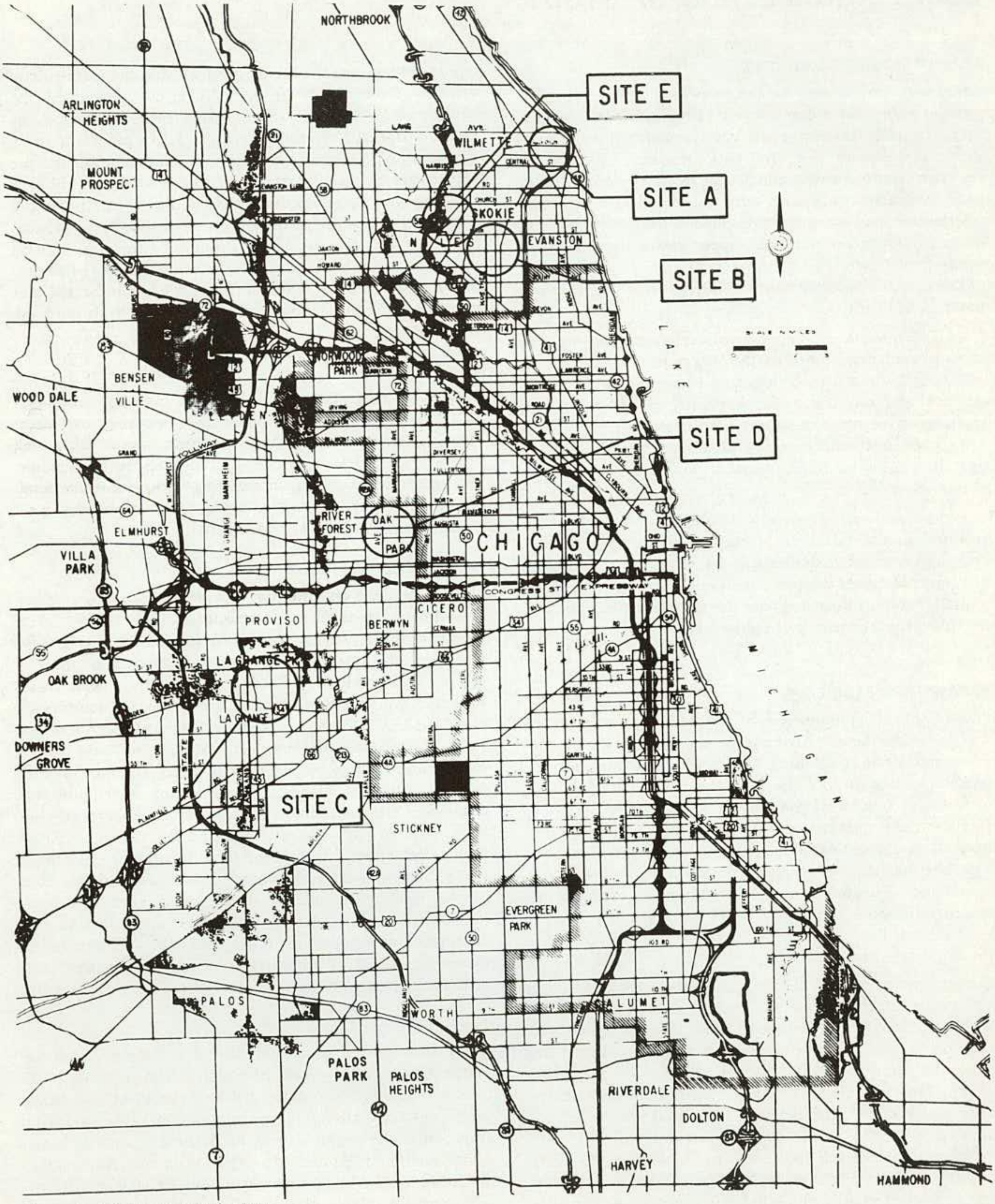


Figure 3. Locations of study sites.

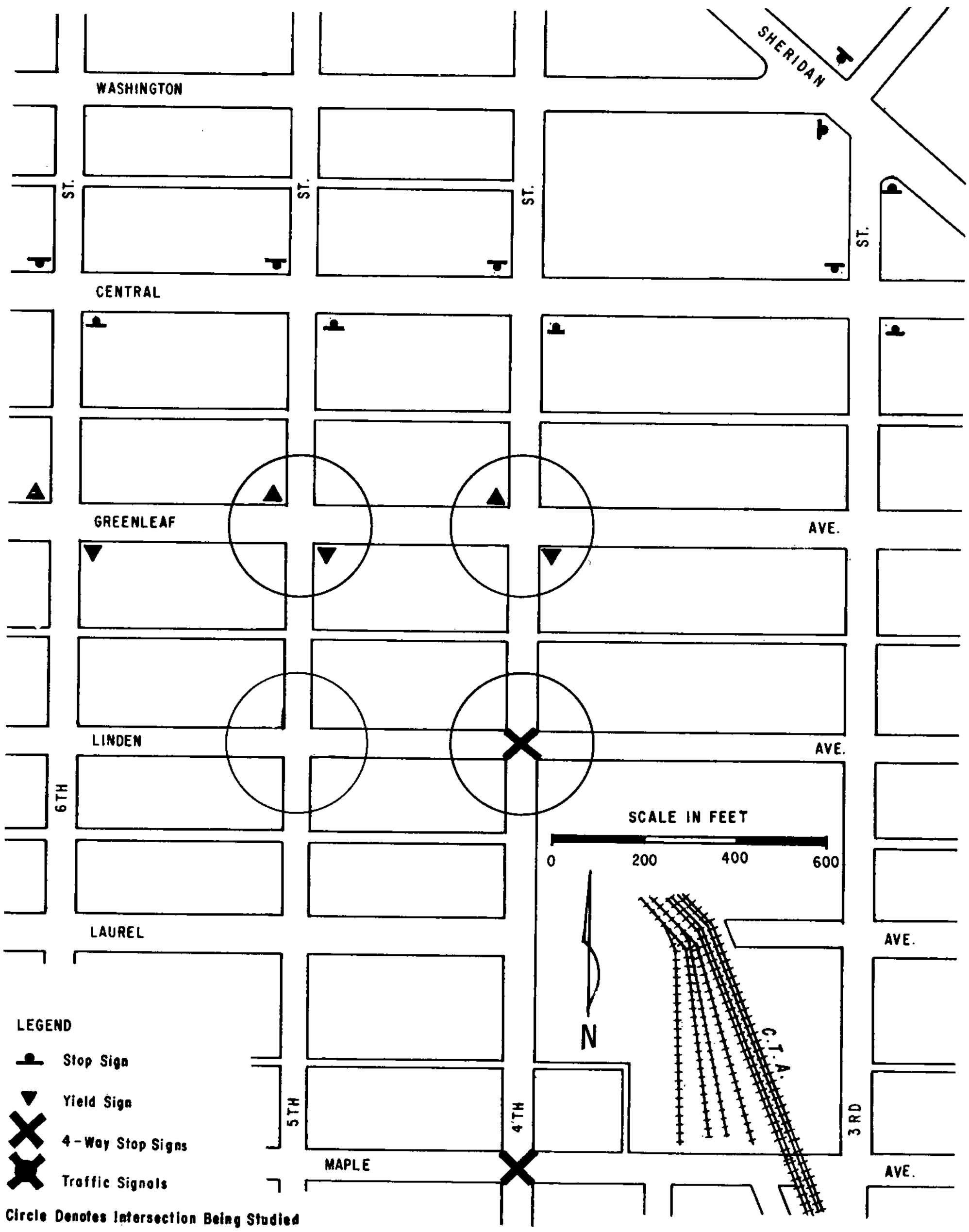
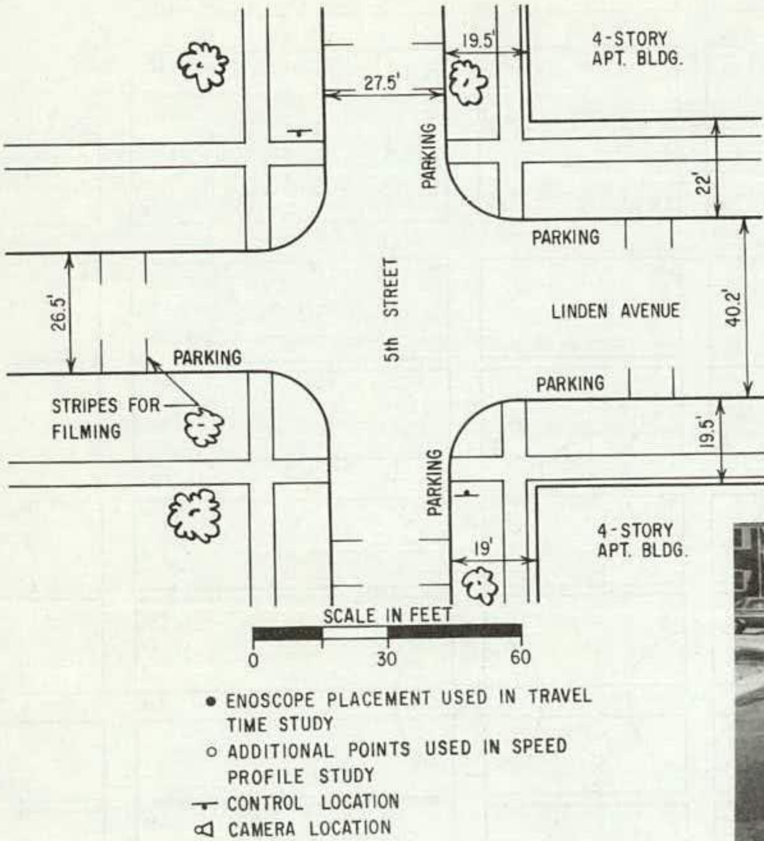


Figure. 4. Wilmette study site (site A) under original conditions.

delayed on the side street as a function of volumes and "critical lag." Keneipp (2.22) compared delay at intersections controlled by two-way STOP and four-way STOP. Inwood and Newby (1.10) reported delay studies at intersections where STOP signs were replaced by YIELD control. Hall (2.14) studied comparative delay with a four-way STOP and a semiactuated signal. Major and Buckley (10.54) used queuing theory to develop a formula describing delay to vehicles entering a traffic stream at an unsignalized point. Kell (5.11), as well as Lewis and Michael (5.14), has developed delay curves from simulation models showing effects of major- and minor-street volumes. Aitken (5.01) obtained results from a simulation study which showed delay to vehicles turning left (British right) into the main stream at an uncontrolled T-intersection. Volk (10.24) studied stopped-time delay at intersections having two-way STOP, four-way STOP and signal controls. Travel time and delay in a street network is also a very important measure of system operation and level of service. This becomes apparent when considering present traffic assignment methods which use link travel time as a major factor in determining vehicle paths in a network. Travel time graphs and contours also aid in pointing out locations of delay within a system. The amount of time expended in a given system is one measure of user costs in the system.



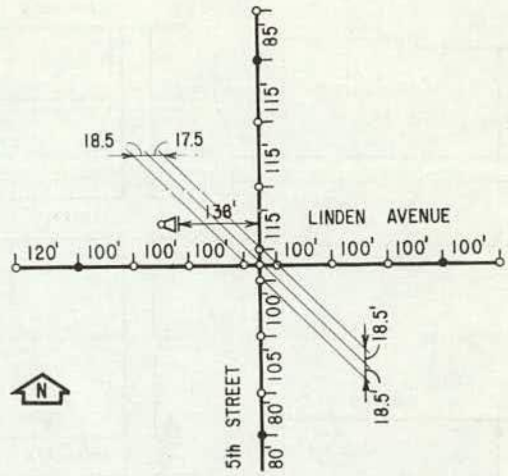


Figure 5. Intersection at 5th Street and Linden Avenue (site A).

Safety

It is generally agreed that safety is of primary concern in measuring the operation of an intersection. Accident prevention was the objective when controls were first applied. An attempt is being made constantly to reduce the number and severity of traffic accidents. The safety characteristics of an intersection can also be described in terms other than accident statistics. Conflicts, various other measures of exposure, driver obedience, hazardous maneuvers, and near accidents all may be used to indicate the potentials for accidents at an intersection. A number of studies have been made to compare the range of intersection controls from none through complete signalization from the standpoint of safety. Numerous studies have been published of accident experience at intersections with different control conditions. Syrek (8.28) reported a comparative study of two-way and four-way STOP control. A Detroit study (8.23) compared accident rate changes at intersections where YIELD signs were installed at formerly uncontrolled locations. Rice (1.20) compared conflict opportunities with accident rates at STOP and YIELD locations. Studies of driver obedience to STOP signs were conducted by Hanson (2.16), Wilkie (2.40, 2.41), and Jackman (2.21).

Headway Distribution in the Traffic Stream

The ability of minor-street vehicles to move across or into the major traffic stream is a direct function of the headway distribution in the stream. A number of studies have been made to describe the distribution of vehicles in a mathematical expression, assuming both randomness of arrival and effects of constrained flow conditions (5.55, 5.59, 10.58, 10.59, 10.61). Little has been done, however, to determine the effect of controls on the distribution of vehicles in that system. Aitken (5.01) has simulated T-intersection operation using vehicle arrival generated by passing the vehicles through a signal upstream from the simulated intersection.

Route Choice

The volumes on each link of a street network (determined by present-day techniques in the traffic assignment process) are obtained by superimposing on the network the paths of a number of vehicles moving between various origins and destinations. This is a close analogy to the actual situation. The path taken is one of several possible choices, and is determined by minimizing a given set of travel criteria. The distribution of vehicles between alternative routes in and through the system can be used as a meas-

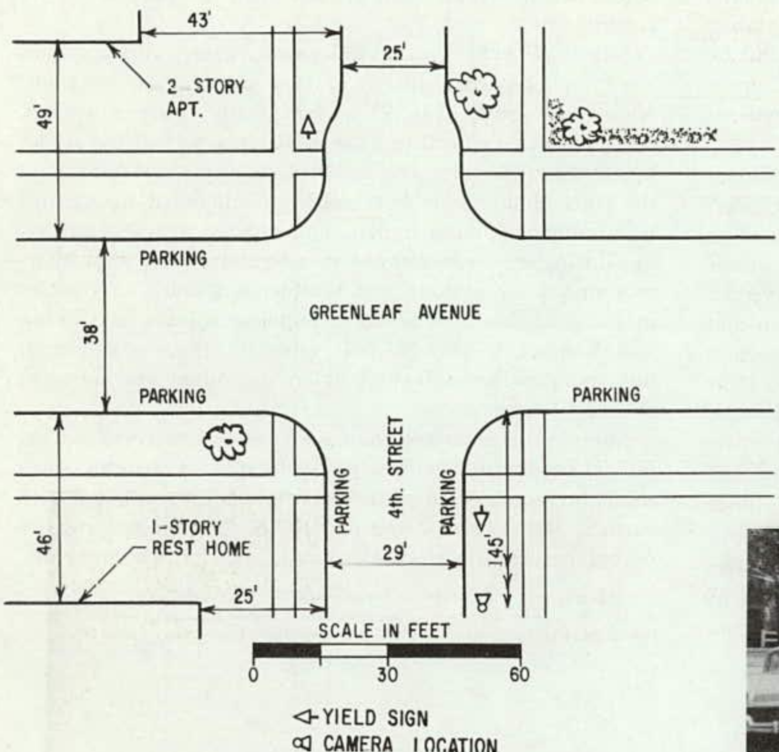


Figure 6. Intersection at 4th Street and Greenleaf Avenue (site A).

ure of the driver's opinion of the relative level of service of each alternative. If all factors could be held constant but one, the effect of variation of that factor on route distribution could be measured. Numerous studies in connection with transportation studies have shown time and distance to be major factors in determining route choice. No information could be located, however, on other possible criteria which might be used by drivers. On a more localized basis, it would be interesting to determine to what extent regulatory devices cause vehicles to use residential or other secondary streets to avoid such devices.

Driver Output

The driver can be thought of as a complicated system which receives a number of inputs, processes them, and emits outputs in a number of forms. It would be desirable to measure such outputs as driver tension, blink rate, steering wheel movements, brake and accelerator application, speed changes, and others, and determine how these are related to operational and physical conditions. Greenshields (10.46) successfully tested the validity of a quality of flow index which incorporated travel time and speed change rates. He later developed an instrument package (drivometer and traffic events recorder) which measured a number of other driver actions and traffic events (6.18). From tests of drivers having various accident records he found the more sensitive driver action measures to be (a) steering wheel reversals, (b) speed changes, and (c) accelerator actions. Platt (6.28) used the drivometer to monitor the effects of driver stress and fatigue as reflected in tracking and speed control. Heimbach (9.08) found that driver actions obtained from the drivometer can be used as a measure of effective distance of highway travel. Michaels (9.14) conducted a study relating galvanic skin response (GSR) to type of route being traveled. Cleveland (9.01) used GSR rate to describe the effect of lighting changes on the driver.

DESCRIPTION OF STUDY SITES

A number of village, city, and state engineers were visited, and more than 500 miles were traveled in the Chicago metropolitan area before the study sites were chosen.

The difficulty in choosing intersections for study was that traffic volumes, because of the nature of STOP and YIELD controls, are relatively low on the minor street. It was important to the studies that data be obtained under a range of volume conditions.

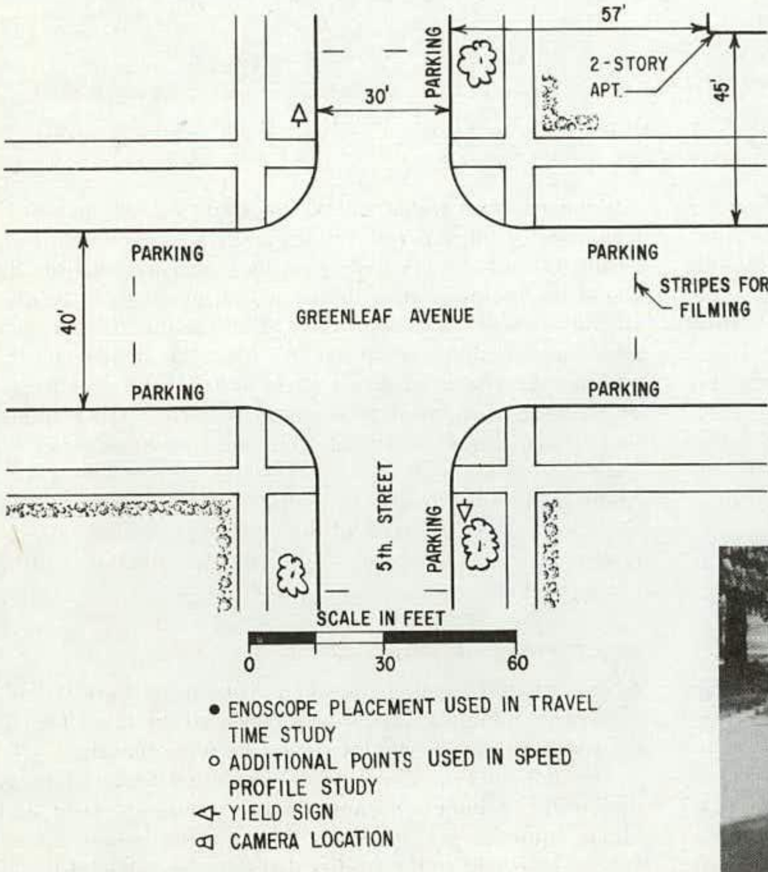
Figure 3 shows the location of the five project study sites. The sites chosen had relatively high volumes, lacked individual peculiarities, and were generally comparable. At certain of these sites, before-and-after studies could be made by changing the existing control situation. Appendix A gives a detailed description of each site and an outline of the study procedures.

Sites A, B and C were chosen for study of individual intersection operation, as well as effects on adjacent intersections. Site A (Fig. 4), in the Village of Wilmette, a suburb north of Chicago, consists of four intersections at the corners of the block formed by Greenleaf Avenue, Linden Avenue, Fifth Street and Fourth Street. Fifth and Linden (Fig. 5) was originally an uncontrolled intersection handling a total of about 415 vehicles in the peak hour from all approaches. Fourth and Greenleaf (Fig. 6) and Fifth and Greenleaf (Fig. 7) are YIELD-controlled intersections accommodating a total of 460 vehicles and 320 vehicles, respectively, during the peak hour. The other intersection, Fourth and Linden, has four-way STOP control and serves 610 vehicles in the peak hour. These four intersections provided information on individual operation as well as the effect on adjacent intersection operation. During the course of the study, Fifth and Linden was converted to YIELD control and then to two-way STOP control.

Site B (Fig. 8), in the Village of Skokie, also a suburb north of Chicago, consists of two adjacent intersections. Kirk and Kostner (Fig. 9) was originally YIELD controlled, but was later changed to STOP control as part of the study. Oakton and Kostner was under four-way STOP control at the start of the study but had been scheduled for change to a vehicle-actuated signal. This change was also carried out during the course of the investigation. The total intersection volume at Kirk and Kostner is about 385 vehicles in the peak hour. The corresponding volume at Oakton and Kostner is about 1,640 vehicles. Data gathered at this site provided information on individual and adjacent intersection operation.

Study of the intersection of Kirk and Kostner was carried out in cooperation with a graduate student working on a thesis project.* Most of his data have been combined with further data gathered specifically for this project and reported herein, therefore eliminating need for comparison.

* Radelat, G., *Comparative Effects of "Yield" Signs and "Stop" Signs on Traffic Approaching a Through Street from a Side Street.* Unpublished Master of Science Thesis, Northwestern University, June 1964.



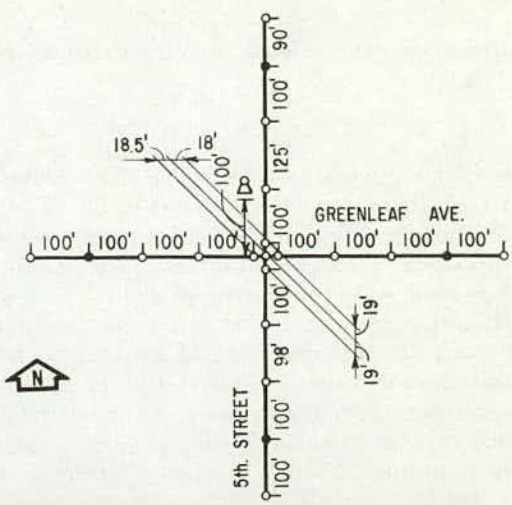


Figure 7. Intersection at 5th Street and Greenleaf Avenue (site A).

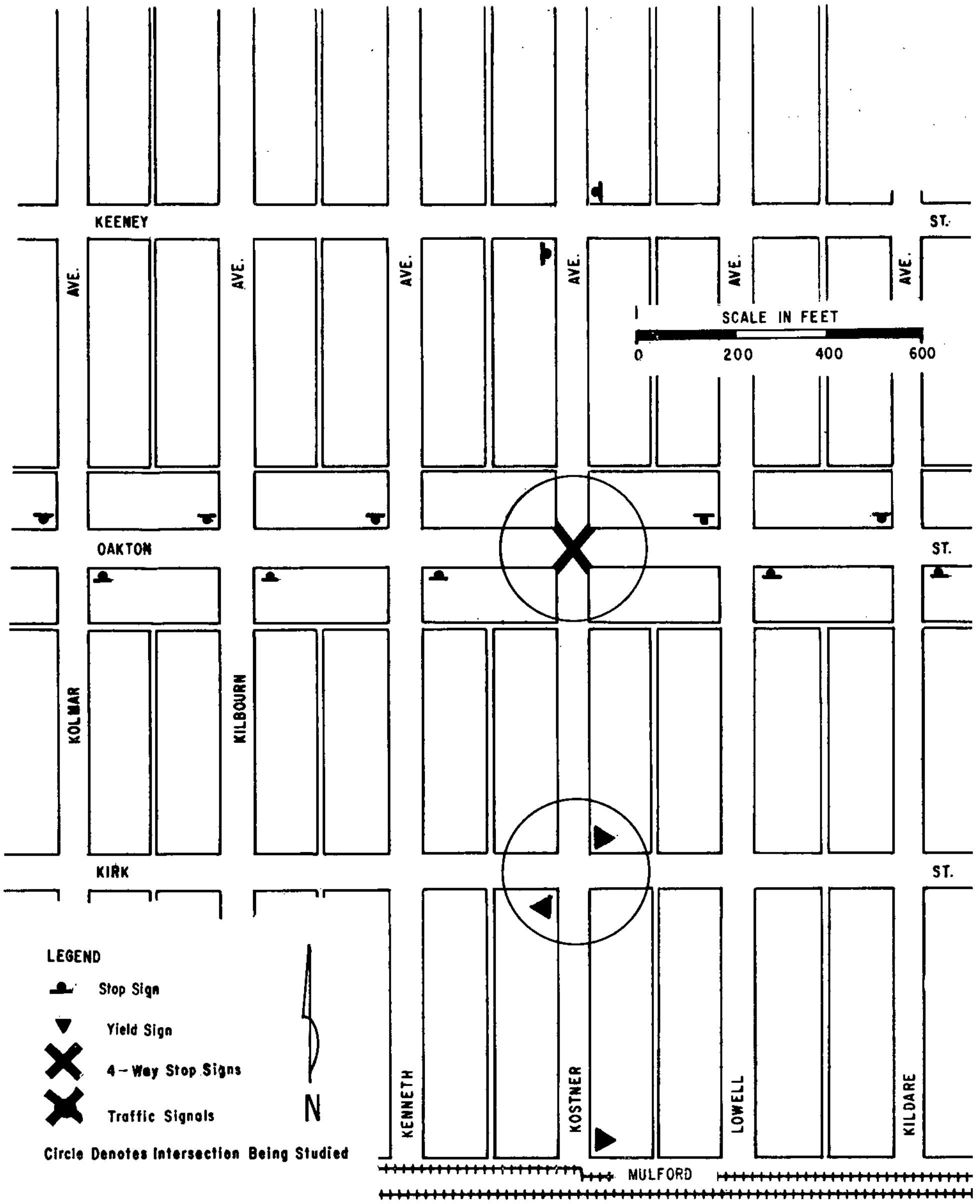


Figure 8. Skokie study site (site B) under original conditions.

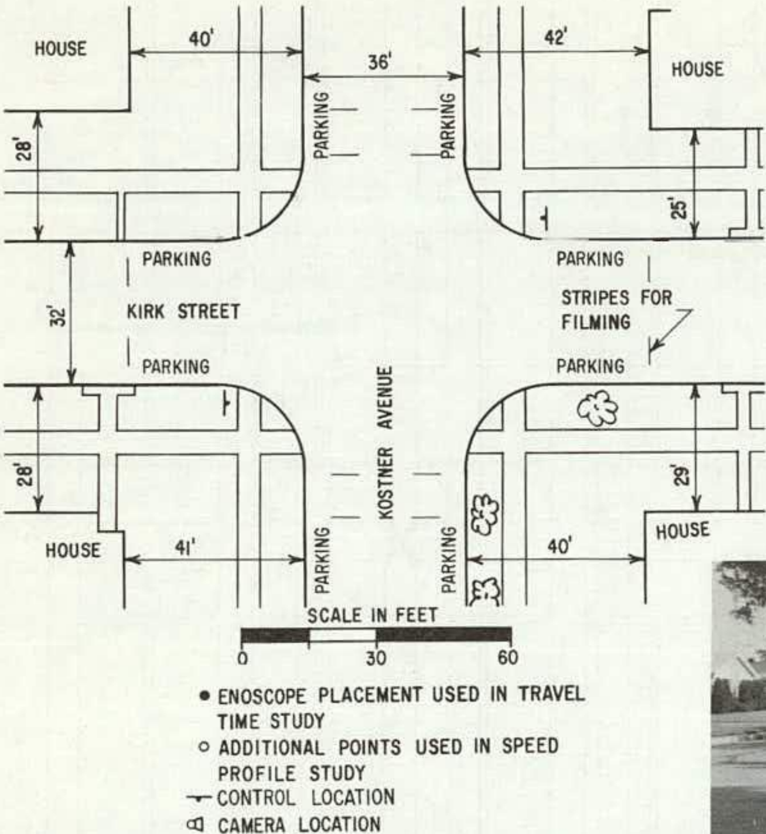
However, he did conduct a number of specialized investigations of the operation at this one intersection. These are referred to in Chapter Seven, along with other comparable studies.

Site C covers the La Grange Park (Fig. 10) and La Grange (Fig. 12) suburban area west of downtown Chicago. Two separate intersections were studied. Kensington and Woodlawn, shown in detail in Figure 11, is YIELD controlled and has a peak-hour volume of approximately 195 vehicles. Cossitt and Ashland is under four-way STOP control and handles a total of about 875 vehicles in the peak hour.

Table A-1 (App. A) lists some of the important traffic and physical features of the individual study intersections.

Site D (Figs. 13 and 14) is in the Village of Oak Park, directly west of Chicago. This site was chosen to study the effect of STOP control on route choice. Drivers moving eastbound between Harlem and Austin Avenues chose routes within the corridor formed by Division and Augusta Streets. Three intersections along Augusta had STOP control on Augusta removed to determine the effect on route choice. At the beginning of the study, Division handled a two-way volume of approximately 700 vehicles in the peak hour, while Augusta carried about 550 vehicles.

Site E (Fig. 15), in the Village of Skokie, was chosen as an alternative in case the "after" study at site D could not be completed because of weather. Because the site D investigation was completed, analysis of information obtained for site E was deferred to a later stage of the project. The study dealt with the use of alternative routes in approaching an expressway interchange.



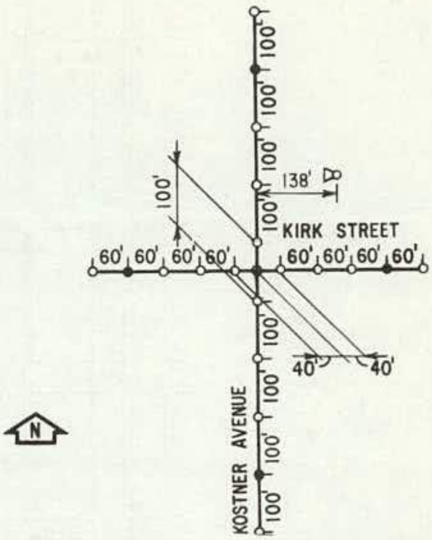


Figure 9. Intersection at Kirk Street and Kostner Avenue (site B).

DATA COLLECTION AND INSTRUMENTATION

Three types of instrumentation were used to gather field data in this study—manual, photographic, and instrumented vehicle. As used here, manual studies include all collection efforts requiring personnel to measure and record data in the field. Some initial testing was made of the 20-pen recorder, but it was decided that it could not be used as effectively as other available methods. Details and use of each specific type of instrumentation are given in Appendix A. The types of instruments used to measure each parameter are discussed in the following.

Speed.—Speed profiles were obtained by the use of stopwatch and enoscope. The enoscopes were placed at measured distances along a leg of the intersection, forming a set of "traps." Vehicles were timed across the traps, and an average speed for each trap was obtained. Such observations were never made concurrently with filming. Speeds of major-street vehicles across the intersection were measured from intersection films.

Volumes.—Peak-hour manual turning movement counts were taken at each individual study intersection during the period of investigation. Manual counts were taken by 5-min periods while speed profiles and travel time data were being collected at each study intersection. No machine counts were used. Volumes were also obtained from the films of each intersection. These were used to determine short period volumes for correlation with delay and gap acceptance characteristics, as well as to have an accurate measure of the volume level during each filming period. During the route study, volumes were taken manually at selected intersections along the major routes under study. Counts were also made in connection with the questionnaire study.

Gap and Lag Acceptance.—Gap and lag acceptance characteristics were taken from the time-lapse photographs of the intersection. The method used in analyzing the films is discussed in the following section and in Appendix B. The acceptance characteristics of each vehicle were correlated with data on speeds and volumes on the major street, which were also obtained from the films.

Travel Time and Delay.—Travel time through the intersection was obtained by the use of stopwatch and enoscope. An enoscope was placed on each leg of the intersection at a point in advance of where the vehicle was first affected by the intersection. The travel time was obtained for a sample of vehicles and correlated with the 5-min volume which was being taken at the same time. Filming was carried out during some periods when travel times

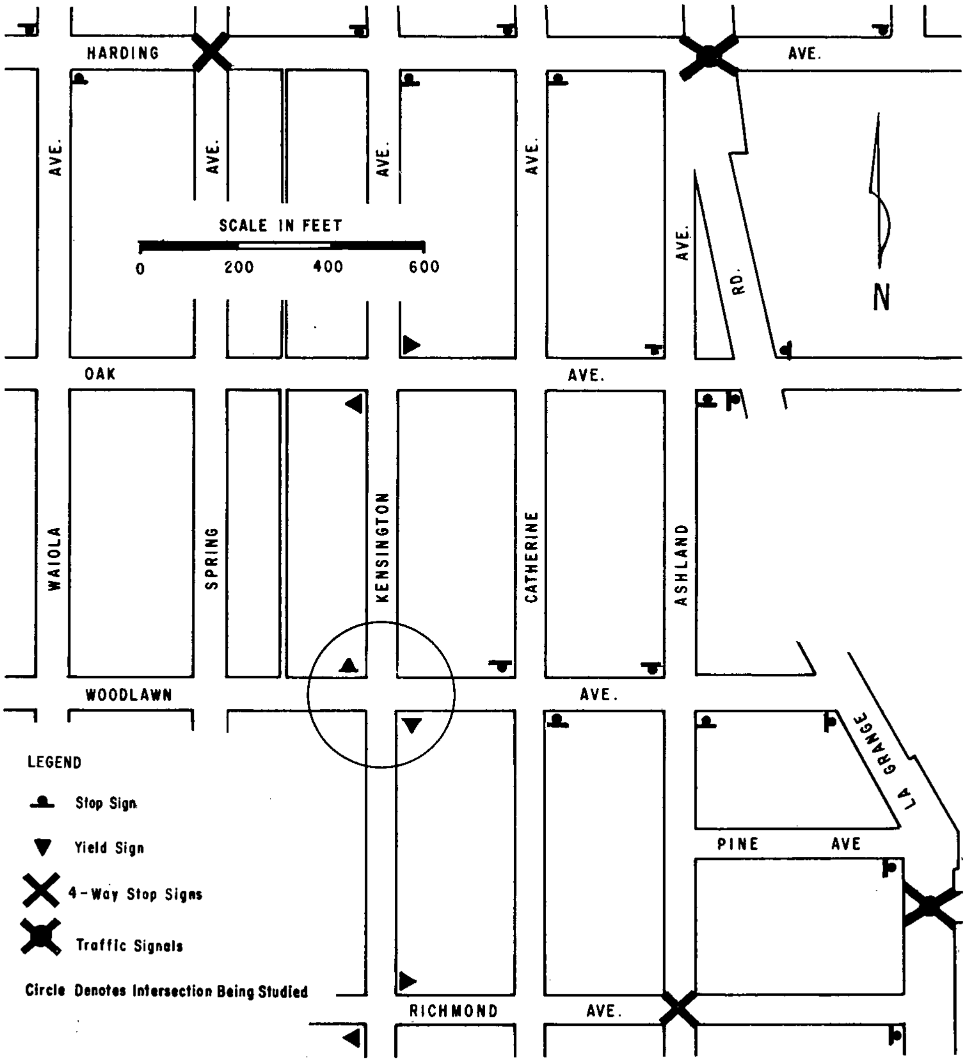


Figure 10. La Grange Park study site (site C) under original conditions.

were being taken. Stopped-time delay, measured directly from the intersection films, was correlated with the intersection volumes also taken from the photographs. A count was made from the films of the number of vehicles delayed in order to obtain a measure of percent unnecessarily delayed.

Safety.—Accident records of the study intersection covering several years were reviewed in order to compare accident experience under various controls. A study was also made of driver obedience from the intersection films.

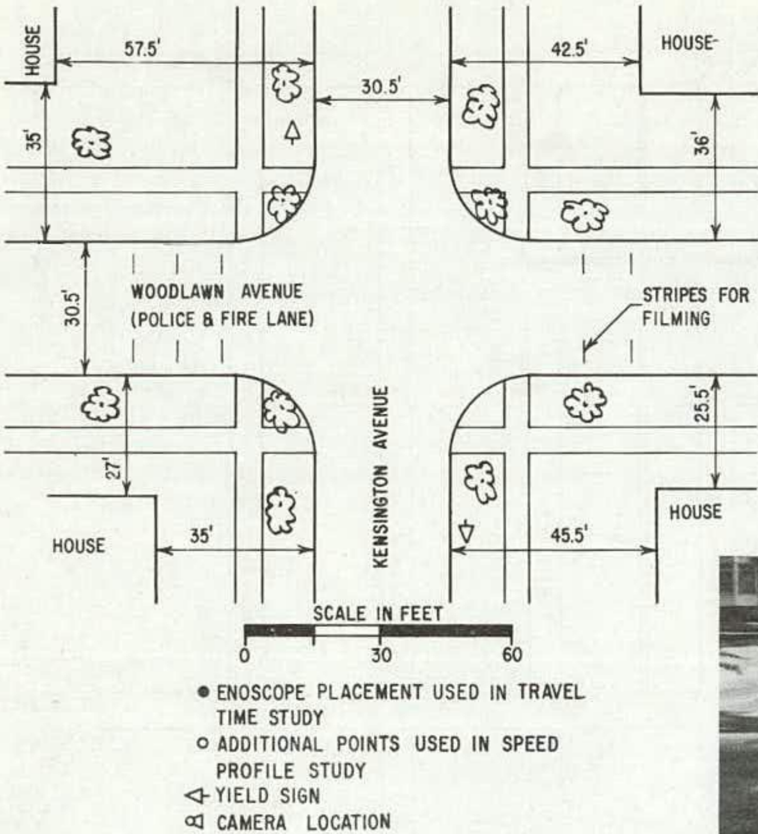
Headway Distribution.—Headways of arrival for all vehicles were measured from the intersection films. Departure headways of pairs of non-turning vehicles also were obtained from the films. The arrival headway and departure headway of the same pair of non-turning vehicles were compared to determine any redistribution that might have occurred.

Route Distribution.—A mail-in questionnaire was used as part of the route study. Its major purpose was to have the driver trace the route he used while traveling through the system. Vehicle counts were also made at important points in the system in order to estimate volume on each section of roadway under study.

Driver Output.—An instrumented vehicle was employed for the system study to determine driver actions along the several routes under study. The vehicle, referred to as the drivometer and traffic events recorder, was loaned to the project by its developer, Dr. Bruce D. Greenshields. A series of instruments attached to the vehicle measure driver actions and vehicle motions. Two drivers were used to drive several times over each route under study. Such items as speed changes, travel time, delay, steering wheel reversals, brake applications, accelerator reversals and direction change were recorded on each route.

ANALYSIS METHODS

Analysis was conducted of data on YIELD- and two-way STOP-controlled intersections only, that on other types of control being deferred to the second stage of the project. Certain noteworthy methods employed in the process in-



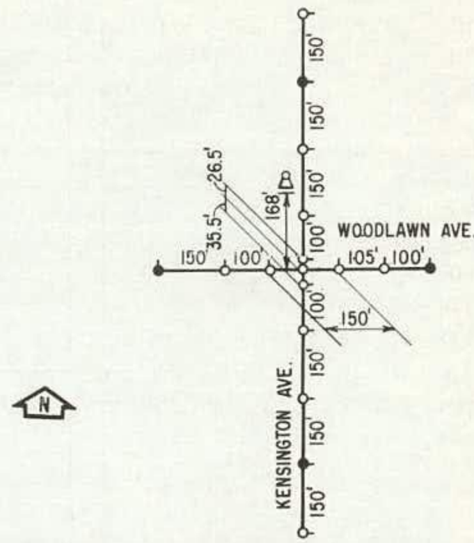


Figure 11. Intersection at Kensington and Woodlawn Avenues (site C).

volved use of specialized equipment and techniques, as well as automatic data processing equipment.

The film analysis was carried out on a modified Kodak Analyst II 16-mm movie projector, which has a control box that allows film to be advanced at 2, 4, 8, 12 or 16 frames per second. The film also may be moved one frame at a time and can be run in reverse as well as forward. Such control allows the investigator to study traffic movements in great detail. A record of frames (time) is kept by use of a built-in frame counter. The projector is equipped with a mirror and ground-glass screen, on which it was possible to superimpose a grid for analysis.

A series of frame numbers was recorded as designated vehicles crossed lines on each approach to the intersection (see Appendix A). On the major street, three lines were used—(a) an arrival line arbitrarily positioned 50 to 100 ft ahead of intersection so as to be beyond the influence of the intersection; (b) the midpoint of the intersection; and (c) the departure line, another arbitrary point at a known distance from the arrival line and also outside the influence of the study intersection. On the minor street, three other points were designated besides the arrival and departure locations—(a) the stop line opposite the control sign; (b) the time at which the vehicle actually stopped, if at all, before going into the intersection; and (c) the time at which the vehicle started into the intersection.

Vehicles on the minor and major streets were numbered separately. Times were taken in terms of frame numbers as vehicles passed the specific points or performed specific actions. The data were recorded by vehicle on sheets designed for this study. The method enabled film analysis to be carried out quickly, without moving the film backward and forward. It was estimated that film analysis time was reduced to less than 50 percent of what would have been required to measure all the data directly in the more conventional manner.

The data sheets were punched on cards for IBM 1401 computer processing in a series of programs written to compute a number of characteristics. One program was developed to obtain gap and lag acceptance characteristics. The lag was determined from the data by taking the difference between the instant the minor-street vehicle was opposite the control and the instant the first major-street vehicle crossed the midpoint of the intersection. The interval between the arrival of that major-street vehicle and the next major-street vehicle, regardless of direction

of travel, was defined as the gap. Each successive crossing of the midpoint by a major-street vehicle formed another gap. The final gap for a minor-street vehicle was formed by the last major-street vehicle to arrive at the midpoint before the minor-street vehicle proceeded, and the first major-street vehicle to pass the midpoint after the minor-street vehicle proceeded. The output of the program contained information on the length of gap or lag in seconds, whether the gap or lag was accepted or rejected, whether or not the minor-street vehicle stopped, and the approach and exit leg of each minor-street vehicle.

Another computer program was written to obtain stopped-time delay for each side-street vehicle. In addition, volumes and average speeds were computed as follows: (a) 5-min volume and average speed, (b) a 10-min volume and average speed, and (c) an observation interval volume and average speed.

The 5- and 10-min periods for each vehicle were centered about the time the vehicle arrived opposite the control. The observation interval was utilized to measure operation parameters during the time in which the driver is able to observe the activity at the intersection as he is approaching and entering it. It is taken as the time during which the driver travels from the previous intersection until he moves across or into the intersection under study. Details on the definitions of these terms and method of determination are given in Appendix B.

A third computer program was developed to determine the headways of arrival and to measure the change in headways of pairs of through vehicles on the minor streets which use the intersection. This program is essentially

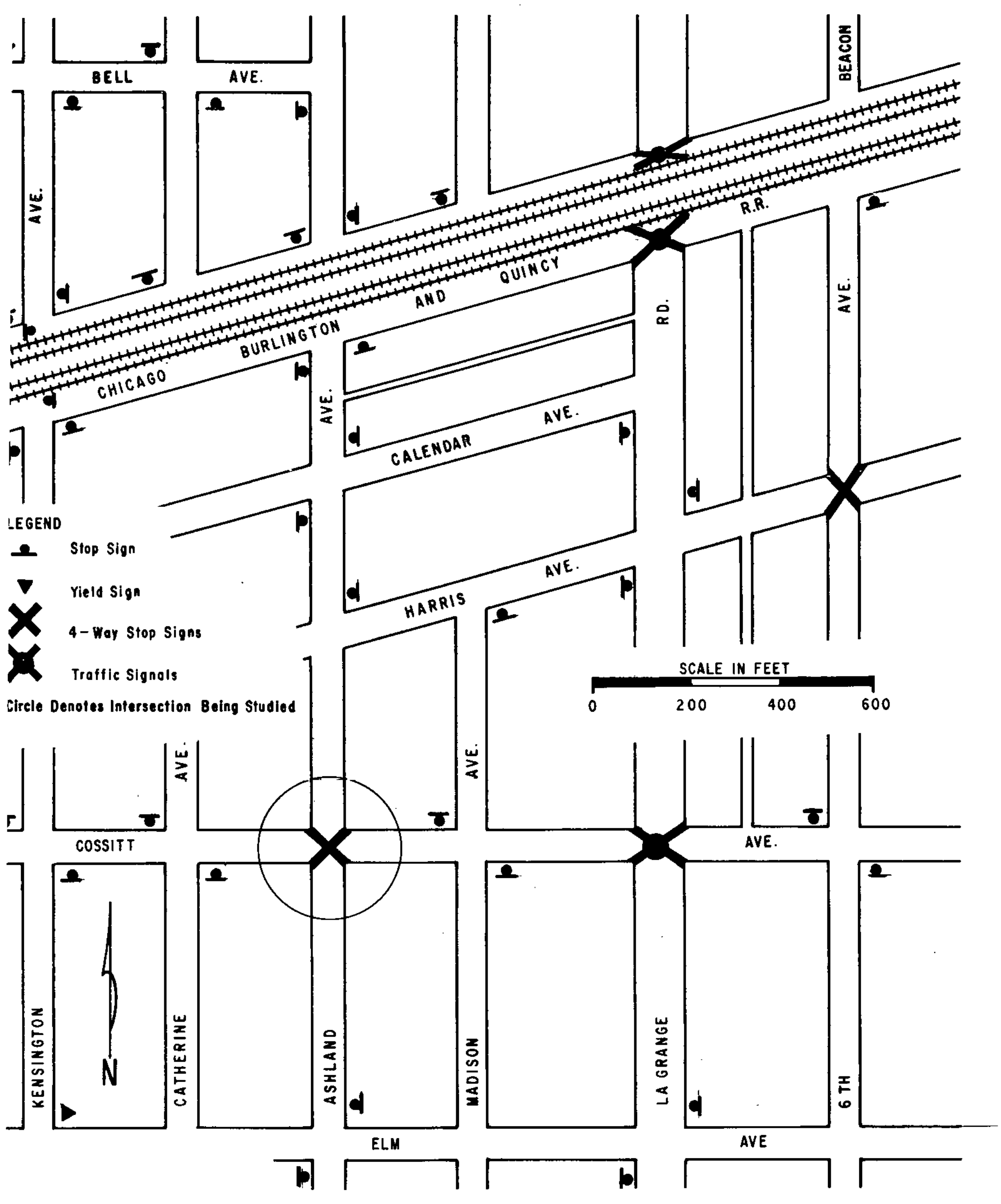


Figure 12. La Grange study site (site C) under original conditions.

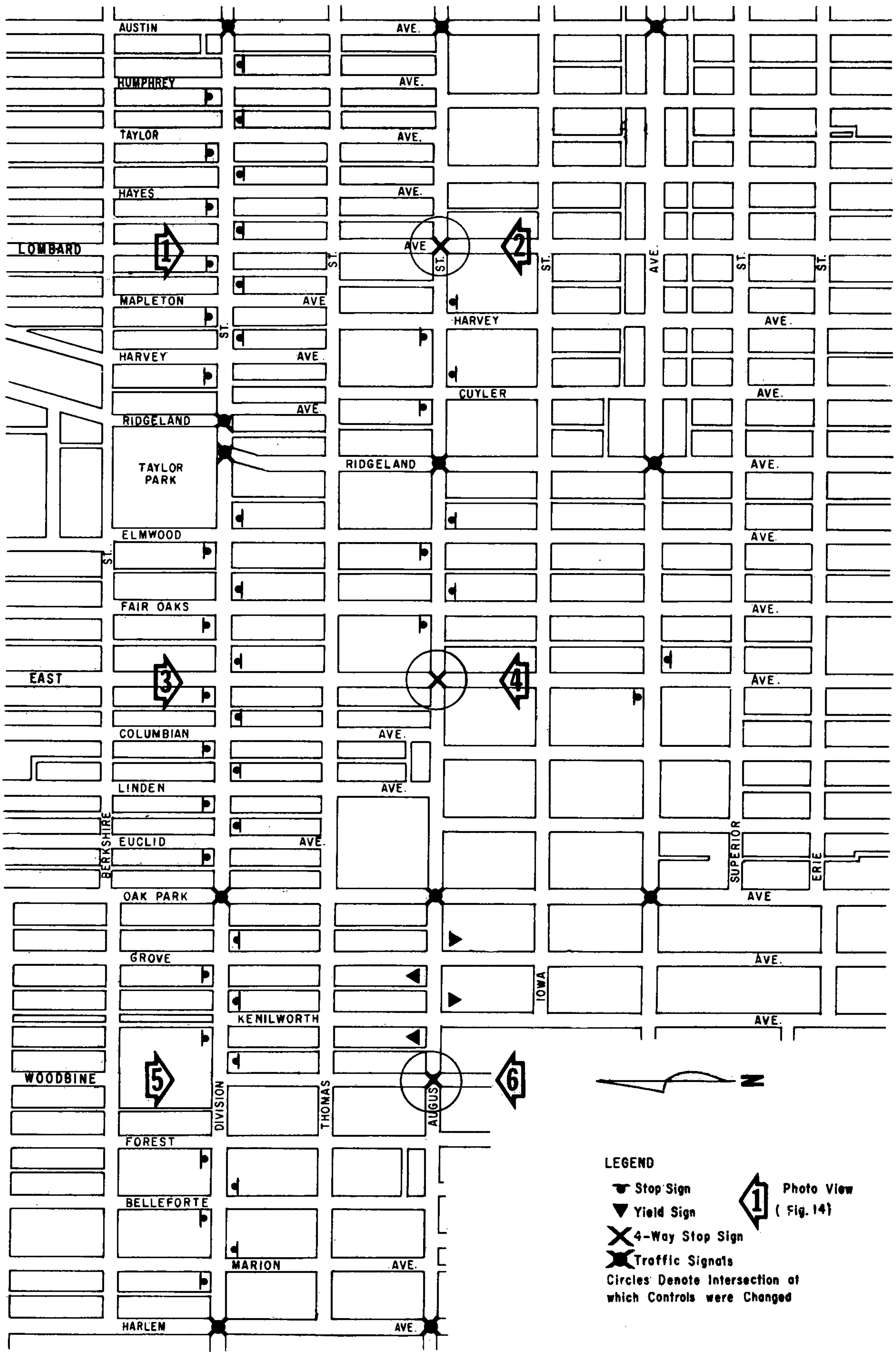
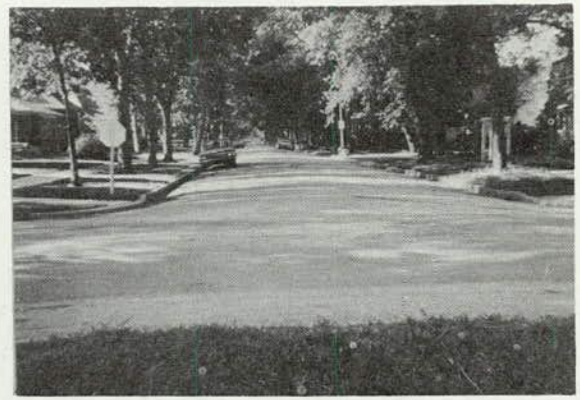


Figure 13. Oak Park site (site D) used for route study.

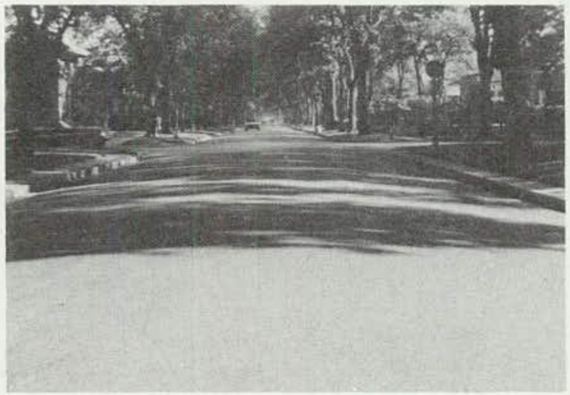
1 LOMBARD AND DIVISION

3 EAST AND DIVISION

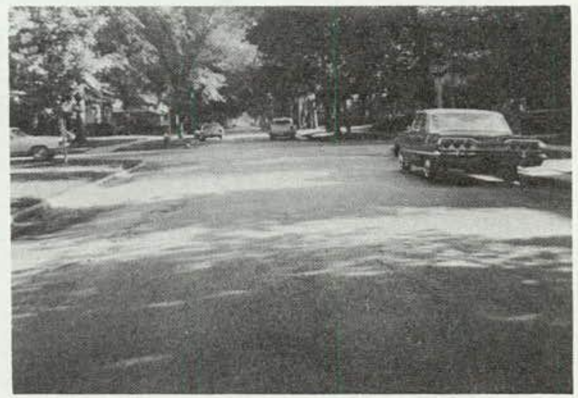


5 WOODBINE AND DIVISION

2 LOMBARD AND AUGUSTA



4 EAST AND AUGUSTA



6 WOODBINE AND AUGUSTA

Figure 14. Intersections of Oak Park study site (site D).

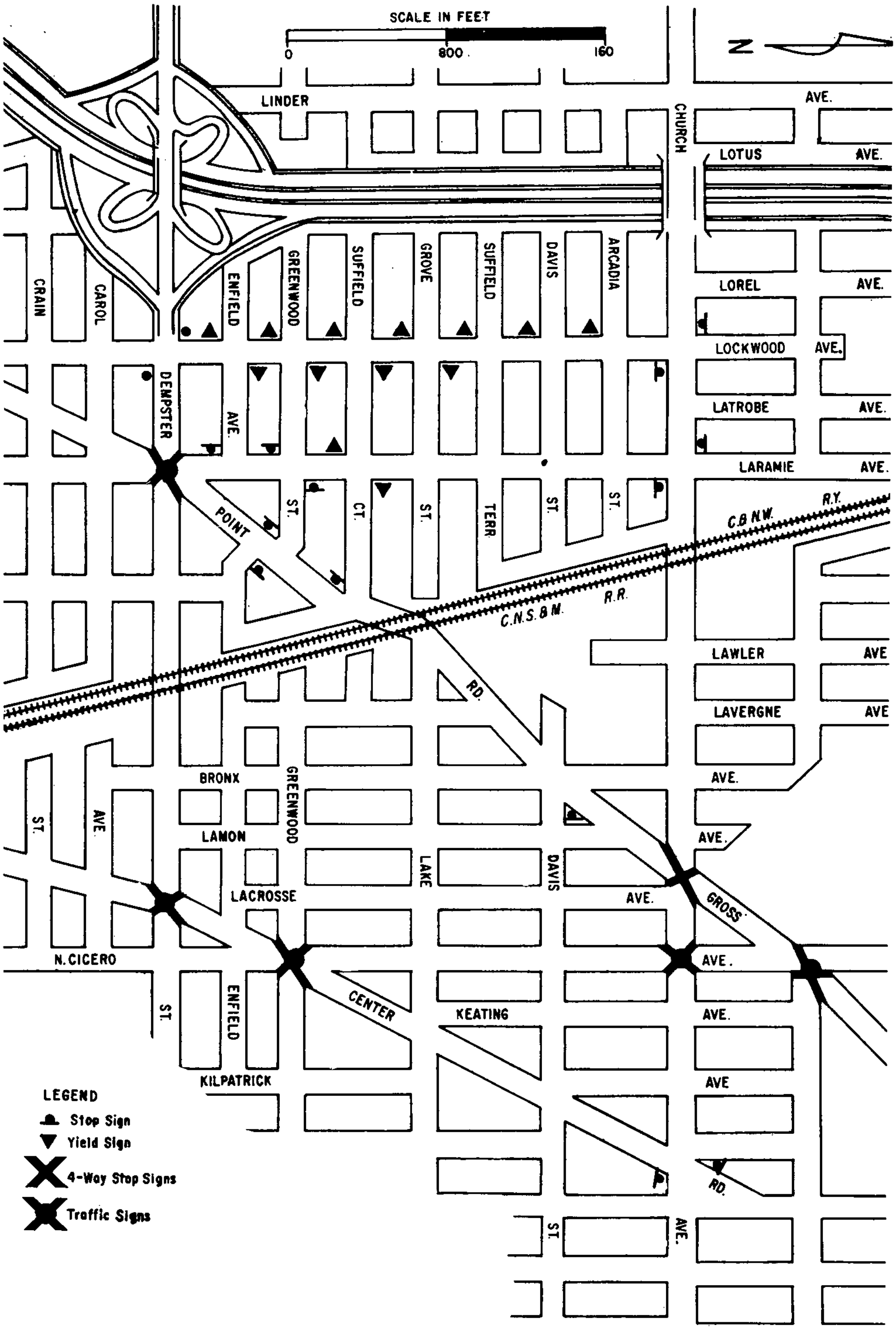


Figure 15. Skokie site (site E) used for route study.

a sorting and tabulating process which can be done on standard data processing equipment.

The general flow diagrams for these programs are shown in Appendix B. Data from the drivometer films were punched directly onto IBM cards and listed. From these data the characteristics of the routes under study were found by adding together the corresponding segments from each test pattern, as measured with the vehicle.

CHAPTER FOUR

RESULTS

The results presented herein are those obtained from analysis of data pertaining to the operation of the YIELD- and STOP-controlled intersections at each of the project study sites. Analysis of uncontrolled, four-way STOP-controlled, and signalized intersection site data has been deferred to the second stage of research. Although the data are limited to a few intersections in one metropolitan area, and in some cases the sample is small, an attempt has been made to combine data to arrive at indications of how patterns in operational behavior vary under YIELD or STOP control. Each intersection studied was in an urban area with all the effects of a surrounding urban environment in play. Therefore, any application of these results should be limited to these same types of conditions.

The primary aim of this analysis has been to test the effectiveness of the various parameters studied in describing intersection operation. The secondary effort was to obtain some preliminary relationships as guides for further study.

INTERSECTION OPERATION

Gap and Lag Acceptance

The information on the acceptance and rejection of gaps and lags was taken from the output of the computer program discussed under "Analysis Methods" (Chapter Three). The flow diagram is shown in Figure B-2 (App. B). It should be noted that in a number of cases the output showed presence of gaps between 0 and 1 sec. Although these were not shown to be accepted, several cases occurred where lags of this size were accepted. The occurrence of a gap below 1.2 to 1.5 sec is highly unlikely under normal flow conditions. Also, the acceptance of lags below 1 sec seems to be unrealistic.

Review of the data and intersection operation revealed that these cases resulted from two factors. The first is that the accuracy of the film was limited to the frame interval of 0.6 sec. Gaps or lags which fell between frames on the film had equal opportunity of being put in either the upper or the lower category. The second factor was the intersection operation itself. Where the small lag was accepted, this represented only one vehicle out of the several hundred studied for the particular condition. Cases such as this were generally a result of some peculiarity of operation which occurred at this intersection when, for example, a major-street turning vehicle would stop and let the minor-street vehicle advance. As a result, the values between 0 and 1 sec were dropped from consideration. The limitation in film accuracy was accepted as a cancelling error as there is equal likelihood that borderline cases will fall in either the lower or the higher group.

The flow diagram of the computer program for determining gap and lag acceptance (Fig. B-2) shows that conflicts having certain turn maneuver combinations between major-street vehicles and minor-street vehicles were eliminated from consideration. Those combinations chosen were of the type where there was a possibility that the minor-street driver was not aware that the major-street driver was going to make the turn maneuver and, had he known in advance, might have changed his decision to accept or reject. Examples of this type of maneuver are shown and discussed in Appendix B.

It was also decided that analysis would not be made of vehicles which moved through a gap or lag immediately behind another vehicle. These vehicles were denoted as "tailgaters" and eliminated from consideration. Classification of these cases was left to the judgment of the observer.

The gaps and lags accepted or rejected by each minor-street vehicle at a particular control were grouped into 1-sec intervals for analysis. Comparisons between acceptance characteristics at YIELD and STOP controls, between gaps and lags, and between peak and off-peak periods were made statistically by comparing percent acceptance for each gap or lag interval.

The acceptance distributions were plotted and compared in a number of ways. Figure 18 shows the combined acceptance distributions for YIELD and STOP control, during both peak and off-peak periods, and for both gaps and lags. It reveals that a greater percentage of drivers will accept any size of gap or lag at a YIELD sign than at a STOP sign. This trend holds for all gap and lag sizes above 3 sec, but statistical significance occurs only at random sizes.

Figure 19 indicates that for the peak period the previous relationship holds only above gaps and lags of 7 to 8 sec. Below this, the trend is reversed so that there is greater acceptance at a STOP sign than at a YIELD sign. On the other hand, Figure 20 shows that there is a general trend in the off-peak period toward greater acceptance at a YIELD sign for headways above 3 sec. This relationship is supported by a reasonably high occurrence of significance of difference at the 95 percent level of confidence. The reversal of expected performance which occurs during the peak period prompted a deeper investigation of the component factors involved. Gap acceptance and lag acceptance were tabulated separately and compared. The effect of peak and off-peak periods on the distribution was also investigated. In order to review these simultaneously, the resulting curves are shown together in a reduced form in Figures 16 and 17: the individual plots of Figure 16 are shown at a larger scale in Figures 18 to 26, those of Figure 17 in Figures 27 to 32.

Figure 16 provides a thumbnail sketch of acceptance characteristics in comparing STOP- and YIELD-controlled intersections. The columns show combined, peak, and off-peak characteristics, respectively, while the rows show gap acceptance and lag acceptance separately and in combination. Figure 16-d shows that for the combined peak and off-peak periods, the gap acceptance at gaps greater

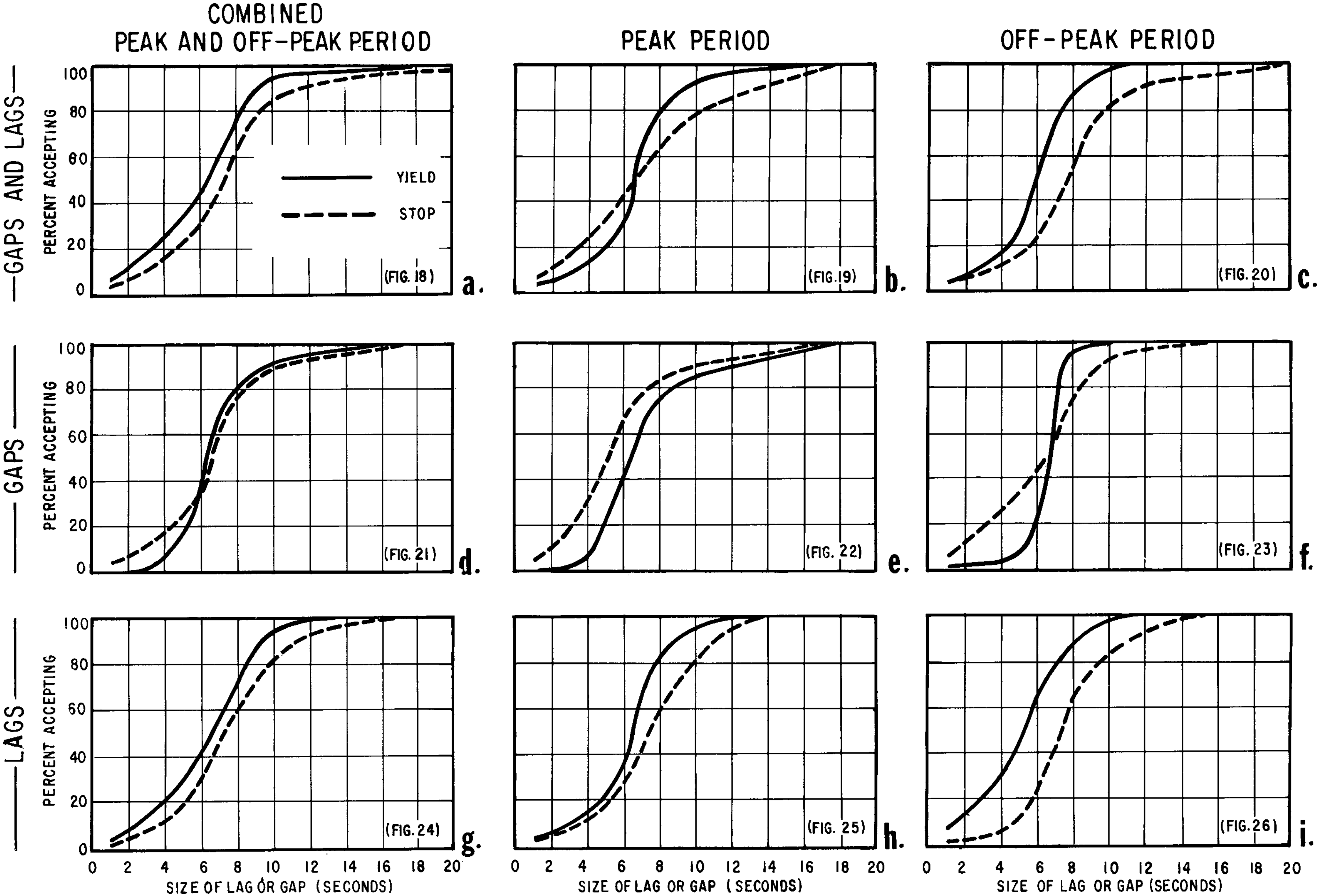


Figure 16. Gap and lag acceptance, YIELD *vs* STOP, *summary of all conditions.*

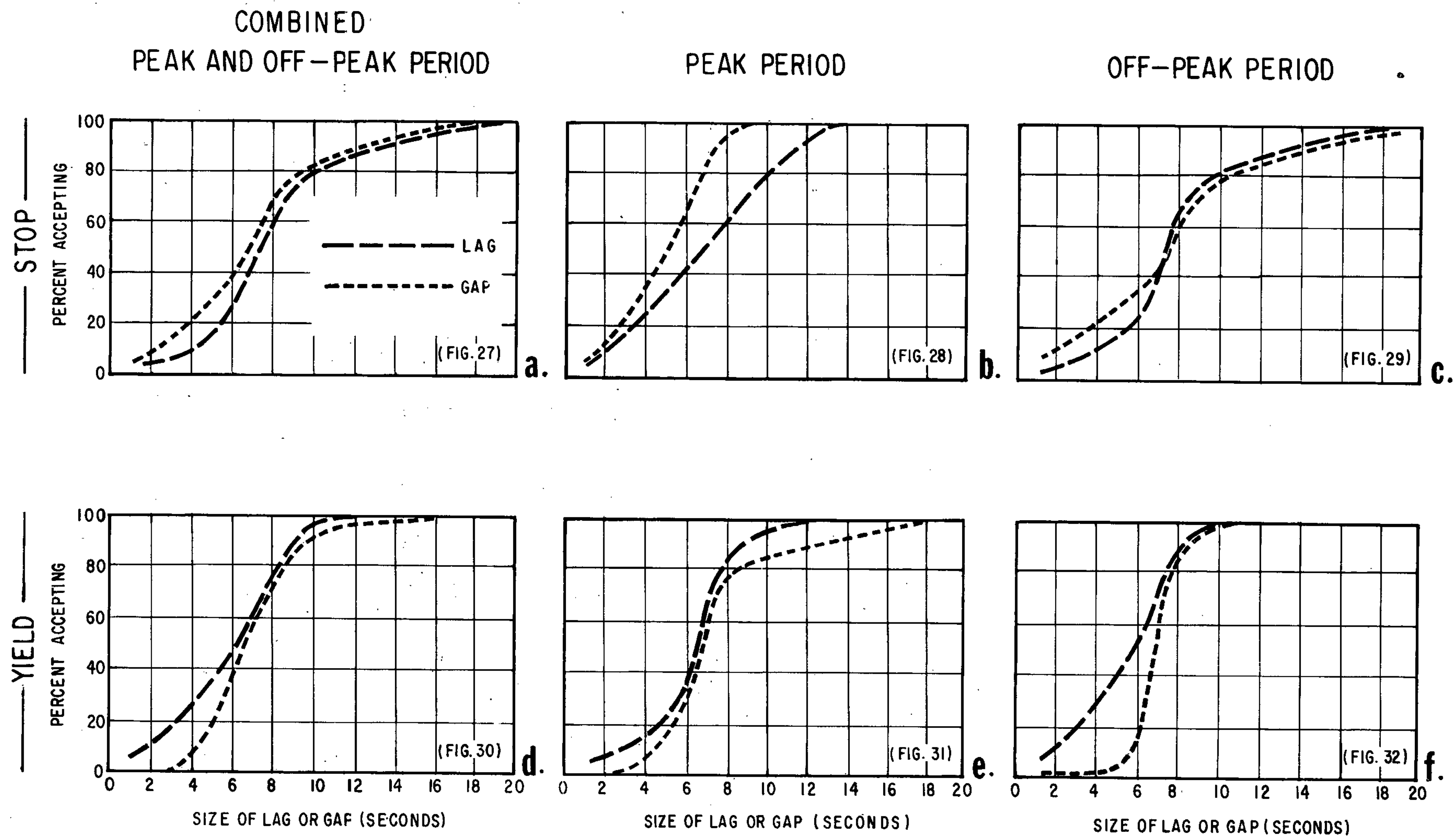


Figure 17. Lag vs gap acceptance, YIELD *vs* STOP*, summary of all conditions.*

than 7 or 8 sec tends to be the same at YIELD and STOP control. Below this, the STOP sign shows greater acceptance of corresponding headways than a YIELD sign. Figures 16-e and 16-f show the same relationship. It should be noted that Figure 16-f is limited in sample size and the curve is not useful other than as a visual aid in locating the proper points. Figure 16-h indicates that for lag acceptance during the peak period, there is a trend towards higher percent acceptance of lags for YIELD control. However, at lags below approximately 6 sec the acceptance characteristics at the two types of control tend to be the same. Figure 16-i shows that lag acceptance during the off-peak period is higher at a YIELD control than for corresponding lags at a STOP control.

It can now be seen how the curves comparing gap and lag acceptance at STOP control and YIELD control (Fig. 16-b) cross at size of about 7 sec. When separated by lag acceptance and gap acceptance the curve for STOP control falls below that for YIELD control when considering lag acceptance at higher lag sizes (Fig. 16-c). However, when investigating gap acceptance, STOP control shows a higher acceptance at lower gap sizes (Fig. 16-h). The combination of this reversal in relationship causes the curves for combined gap and lag acceptance to cross.

The occurrence of significance of difference between percent acceptance of the gaps or lags under different controls and other conditions is sporadic. It is necessary to consider the trends, therefore, stating for the moment that increased sample size would either strengthen or dissipate these trends. The trends pointed out in the foregoing can be seen on the larger-scale figures.

Figures 17-a, 17-b and 17-c compare gap and lag acceptance at the STOP-controlled study sites. In general, all three tend to show that for gaps and lags below 9 or 10 sec there is a higher acceptance of gaps than lags of a corresponding size during all periods. Above this size, and below 4 sec, the curves tend to coincide. This means that there is a range of sizes at which gap acceptance is higher than lag acceptance at a STOP-controlled intersection. The range is greater for the peak than for the off-peak period. It should be noted that according to the manner in which the gap and lag were defined, this is also a comparison of stopped and moving vehicles, respectively.

Figures 17-d, 17-e and 17-f show a comparison of gap and lag acceptance at YIELD locations. There is an obvious trend toward greater acceptance of lags than corresponding gaps below about 7 sec. This relationship has a tendency to hold also for higher values of gaps and lags during the peak period, but the small sample does not allow a statement concerning the off-peak period.

Summarizing Figures 16 and 17, the results show a general trend toward equal acceptance characteristics of drivers considering small lags at both YIELD- and STOP-controlled intersections during the peak periods. The similarity disappears during off-peak periods where the driver at the YIELD control seems to realize an advantage at all lag sizes below 20 sec. Furthermore, there is a definite trend toward lower acceptance of gaps at a YIELD control than at a STOP control for corresponding gap sizes.

The variations of driver gap and lag acceptance exhibited in the various acceptance distributions discussed in the foregoing are probably explained by such operation factors as the period of the day, the type of control, whether the driver is considering a gap or a lag, and the nature of the crossing stream.

Figures 16 and 17 indicate the suggested effects. The operational factors seem to cause the relationship discussed for these figures because of three considerations: (a) the driver approaching the YIELD sign is in a dynamic situation while deciding whether to accept or reject an available lag, and is further faced with the *prima facie* law, which states that his involvement in an accident after not yielding is proof of guilt; (b) the driver, when faced with a situation requiring a quick decision, will tend to yield or remain stopped rather than chance involvement in an accident, but after having some time to adjust to the situation and to consider the problem, may be bolder in his actions; (c) a driver approaching a STOP sign apparently concludes that he will not be able to accept short lags and, therefore, approaches the intersection preoccupied with finding an acceptable gap.

One plausible explanation of these relationships is that when approaching the type of major street considered in this study, a driver during the off-peak periods is not likely to have more than one vehicle approaching on the major street. While the driver is approaching a YIELD control, he must consider that vehicle and decide whether or not to accept that lag. This requires eye motion to each approach and then concentration on the approaching major-street vehicle. The time required to perceive, process and make a decision on this information is not as great as it would be during the peak period, where the likelihood is that there will be more than one vehicle approaching on either one or both legs of the major street. As indicated in the figures, the total peak-hour intersection volume averaged about 425 vehicles, whereas the off-peak-hour volume averaged approximately 225 vehicles. The increased processing time, and the fact that the decision must be made while in motion, tends to lower the probability of acceptance of that lag. This is confirmed in Figures 16-h and 16-i. The trend toward lower acceptance of gaps at YIELD signs, shown in Figure 16-e and hinted at in Figure 16-f, possibly indicates that the driver at the YIELD control needs a longer recovery time to accept a gap after having rejected a lag. This could be caused by quick deceleration plus the fact that the driver has been concentrating on the lag and not giving much consideration to the gap following. However, if the driver approaching the STOP sign is concentrating on the gaps, having immediately eliminated the lag from consideration, he is prepared to take full advantage of the gap available and requires no recovery time. In all cases, it is apparent that these effects occur only in the lower range of gaps and lags. It seems likely that there is some gap or lag size above which the driver does not feel pressed while accepting. Above this, the curves for YIELD and STOP control will tend to coincide. This study indicates that this point is higher for lags than for gaps.

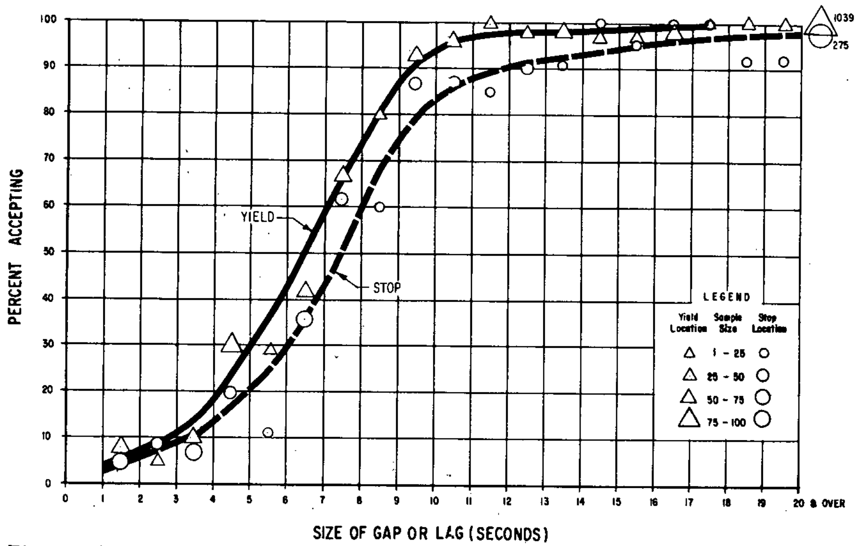


Figure 18. Gap and lag acceptance, YIELD *vs* STOP, *combined peak and off-peak periods, all intersections.*

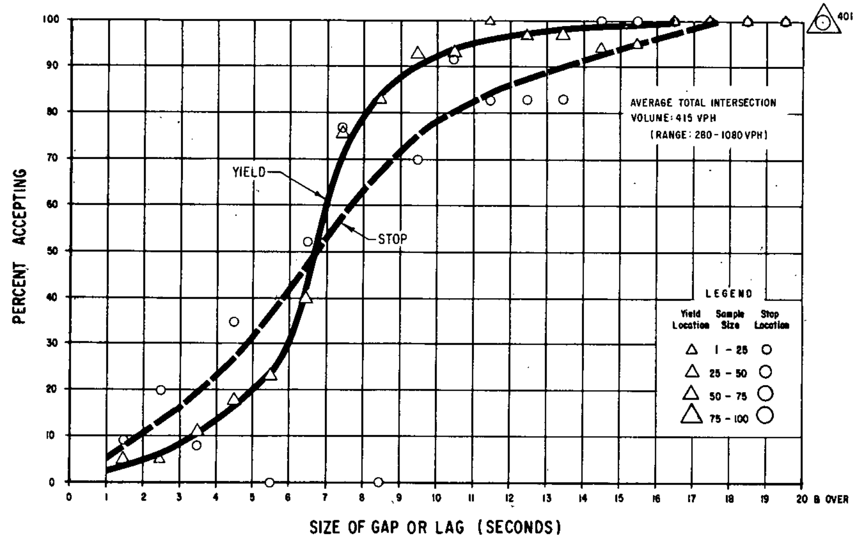


Figure 19. Gap and lag acceptance, YIELD *vs* STOP, *peak period, all intersections.*

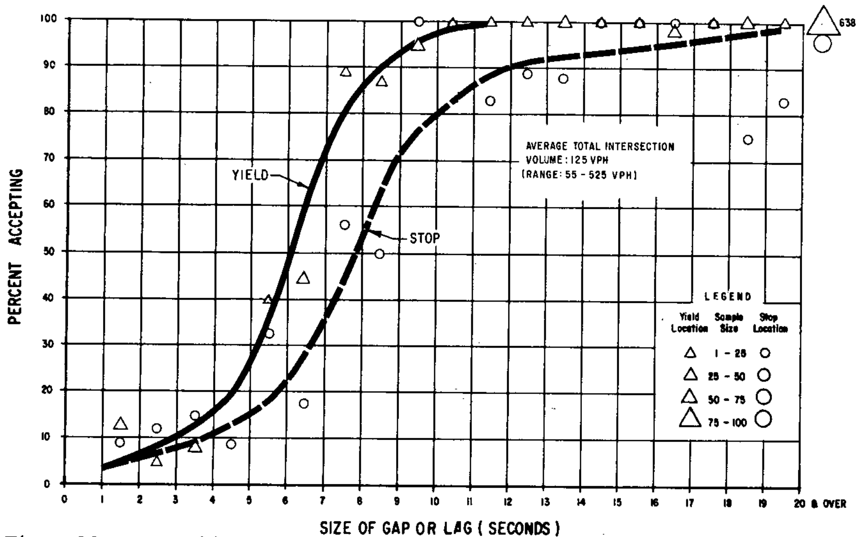


Figure 20. Gap and lag acceptance, YIELD *vs* STOP, *off-peak period, all intersections.*

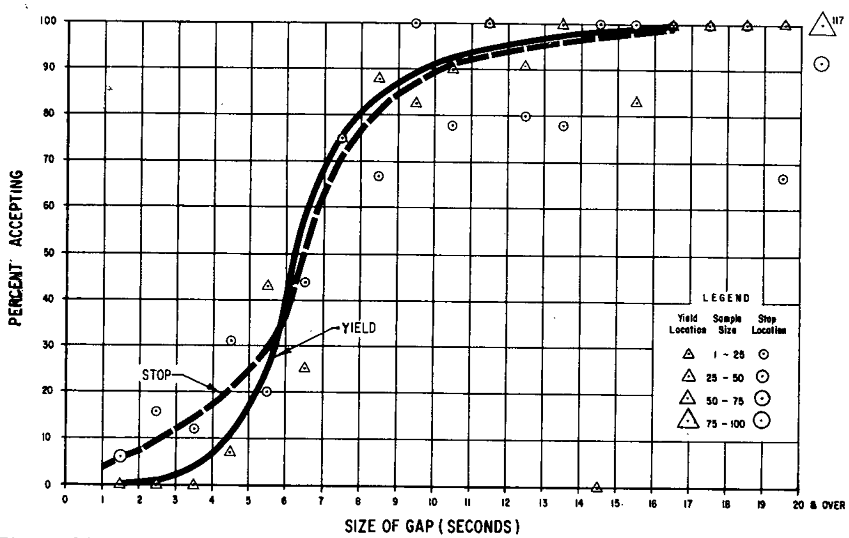


Figure 21. Gap acceptance, YIELD *vs* STOP, *combined peak and off-peak periods, all intersections.*

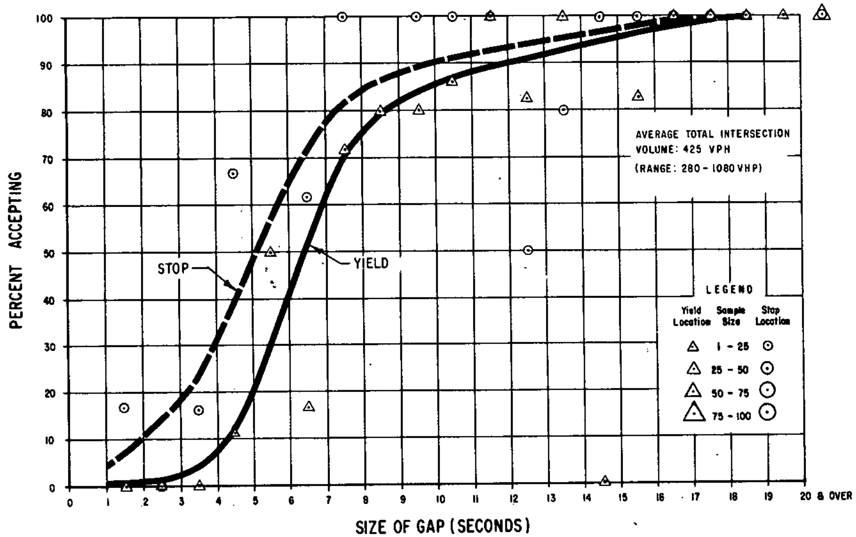


Figure 22. Gap acceptance, YIELD *vs* STOP, *peak period, all intersections.*

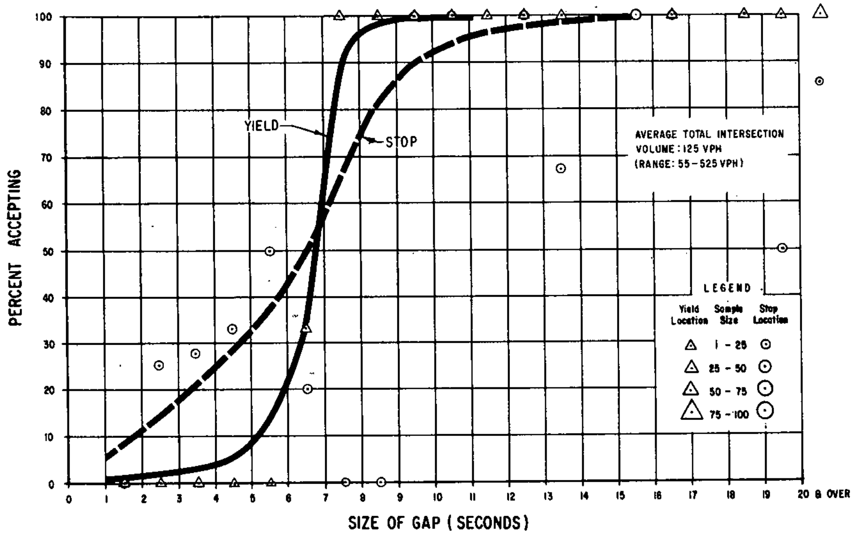


Figure 23. Gap acceptance, YIELD *vs* STOP, *off-peak period, all intersections.*

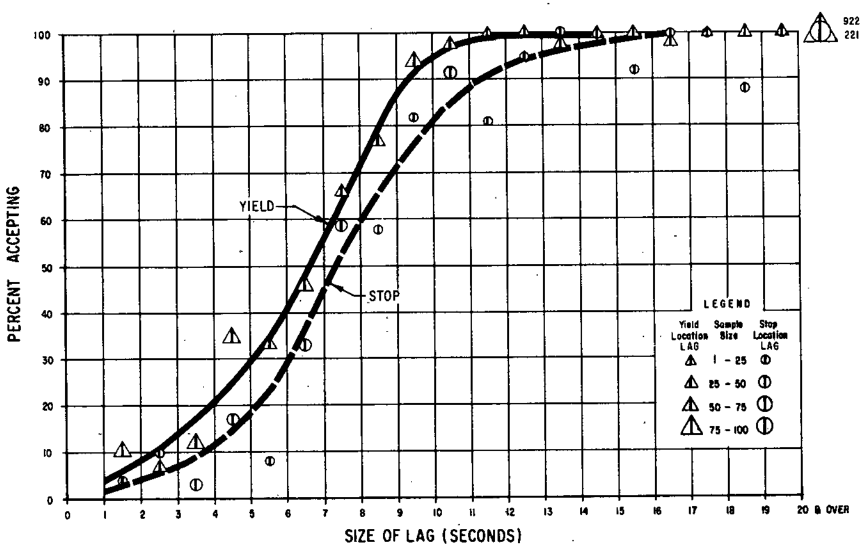


Figure 24. Lag acceptance, YIELD *vs* STOP, *combined peak and off-peak periods, all intersections.*

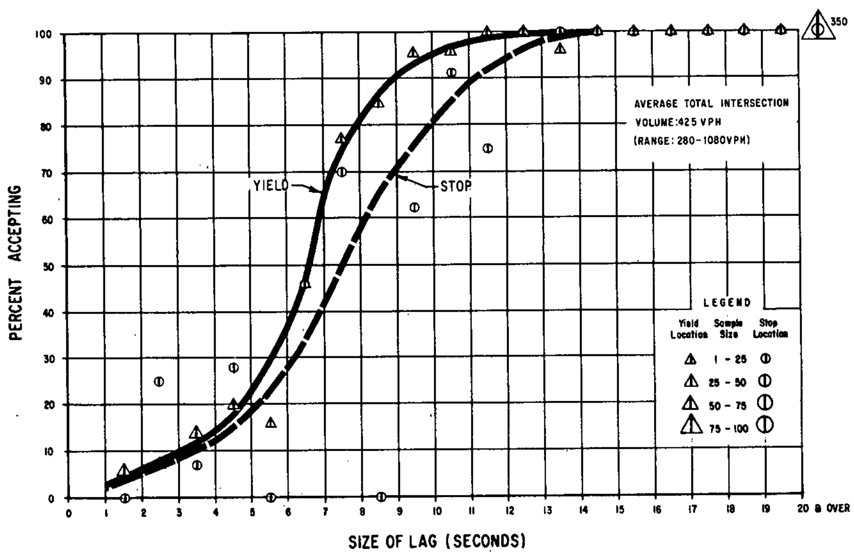


Figure 25. Lag acceptance, YIELD *vs* STOP, *peak period, all intersections.*

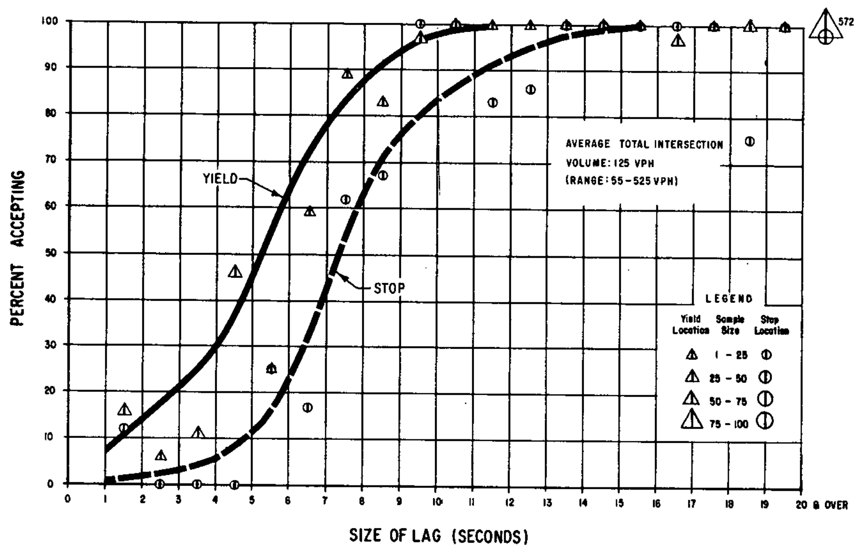


Figure 26. Lag acceptance, YIELD *vs* STOP*, off-peak period, all intersections.*

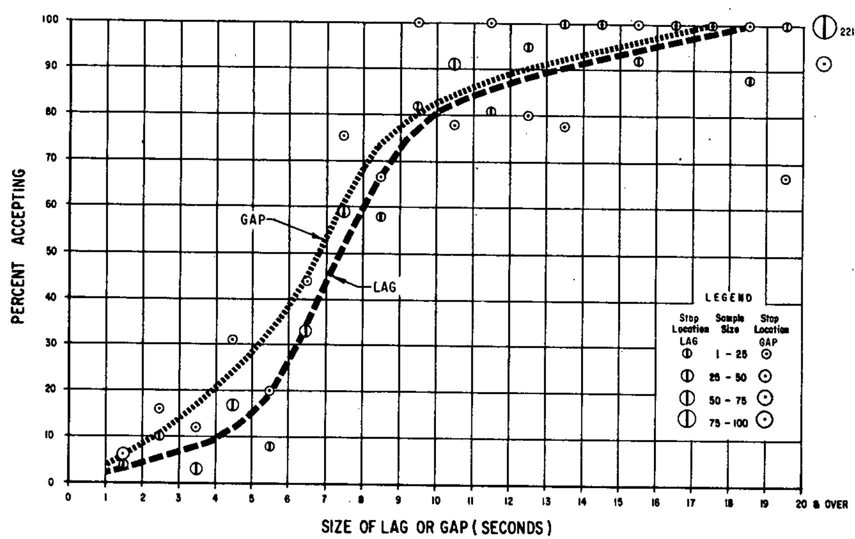


Figure 27. Lag vs gap acceptance, STOP *control, combined peak and off-peak periods, all intersections.*

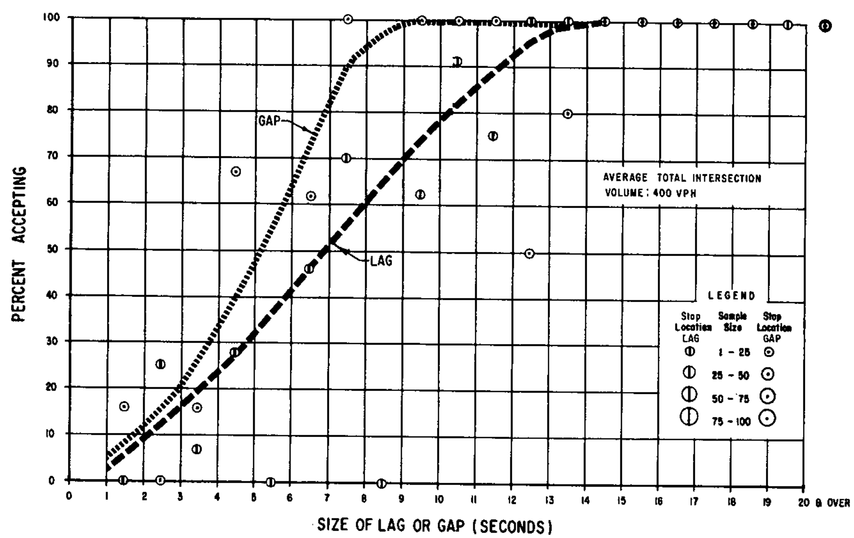


Figure 28. Lag vs gap acceptance, STOP *control, peak period, all intersections.*

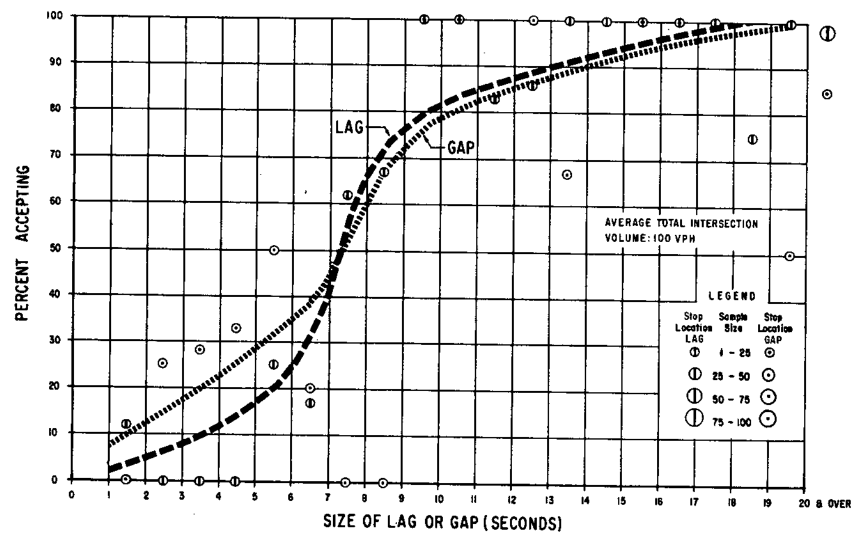


Figure 29. Lag vs gap acceptance, STOP *control, off-peak period, all intersections.*

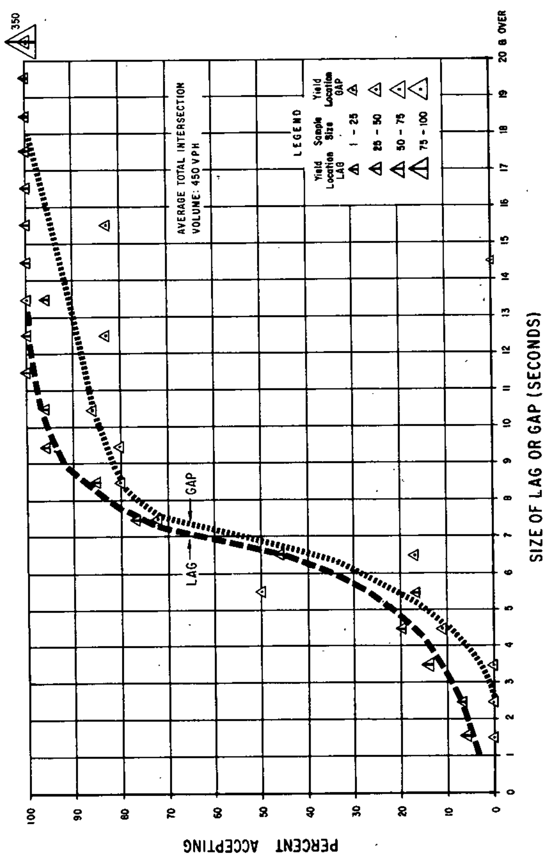


Figure 31. Lag vs gap acceptance, YIELD *control, peak period, all intersections.*

Comparison of gap acceptance and lag acceptance at each type of control (Figure 17) also indicates that this reasoning is sound. The curves show that there is generally higher acceptance of gaps than lags in the lower sizes with STOP control. This indicates the driver preoccupation with gaps. Furthermore, there is the expected trend toward higher acceptance of lags than gaps with YIELD control. This occurs to a greater extent in off-peak than in peak periods, again showing the likelihood of the effect of volume on acceptance characteristics.

It is important to note the variation of acceptance characteristics between the sites where the data were obtained.

Figure 33 presents the gap and lag acceptance characteristics for Fifth and Linden, as well as Kirk and Kostner, while each was under STOP control. Figure 34 shows the gap and lag acceptance characteristics for the intersections of Fifth and Linden, Kirk and Kostner, Fifth and Greenleaf, Fourth and Greenleaf, and Kensington and Woodlawn under YIELD control.

Figure 33, comparing STOP control at the two locations, shows a definite trend toward a lower acceptance of gaps and lags below 8 or 9 sec at Kirk and Kostner. At gaps and lags above this, the curves coincide.

Analysis of the relative positions of the five curves for YIELD control (Fig. 34) reveals some interesting relationships. In the gap and lag range of 5 to 8 sec the curves for each of the intersections are parallel. Above this range the curves tend to coincide. Below this range only

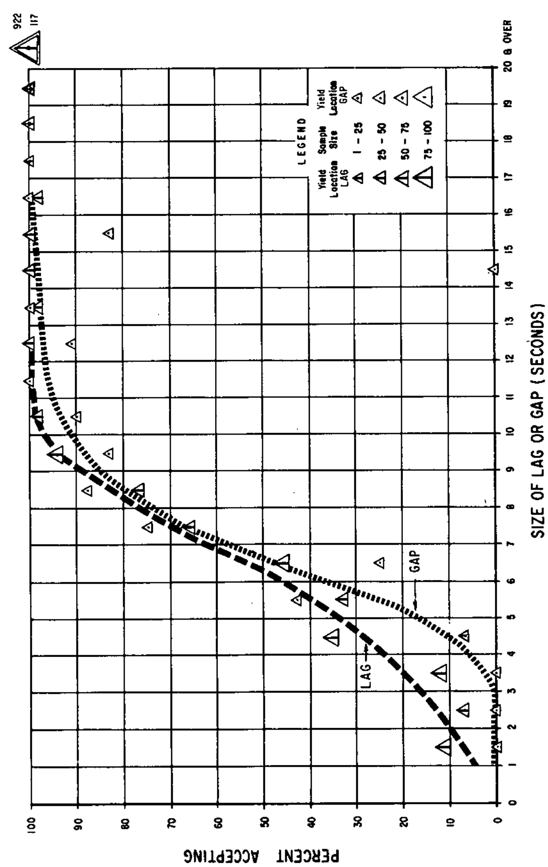


Figure 30. Lag vs gap acceptance, YIELD *control, combined peak and off-peak periods, all intersections.*

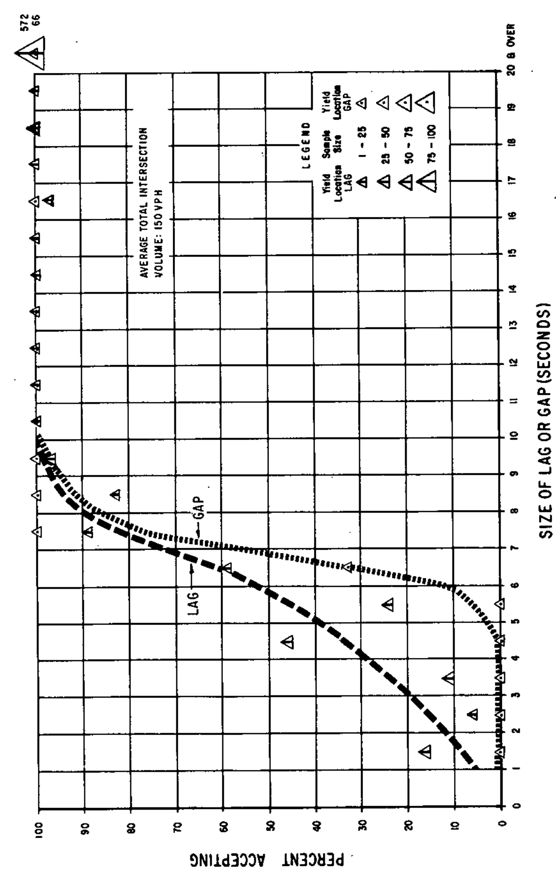


Figure 32. Lag vs gap acceptance, YIELD *control, off-peak period, all intersections.*

the lower three curves are defined. The curve which is the highest of the three at a 4- to 5-sec gap and lag size falls below the other two by the time the 2- to 3-sec size is reached.

Inspection of the middle range of gap and lag sizes shows that Kensington and Woodlawn has the highest acceptance, followed by Fourth and Greenleaf, Fifth and Linden, Kirk and Kostner, and then Fifth and Greenleaf. In the lower headway range, Kirk and Kostner shows the highest acceptance, followed by Fifth and Greenleaf, with Fifth and Linden dropping off to zero at gaps and lags between 2 and 3 sec.

Further data on individual intersections are shown in Figures 35 and 36 for the two intersections where control changes were carried out during the course of the study.

Figures 33 to 36 show the effect of the nature of the crossing stream, as well as of sight distance restrictions. Figure 33, Fifth and Linden, although showing higher acceptance than Kirk and Kostner for STOP control, has the greater sight distance restriction. However, Kostner is an arterial street which is generally protected along its length and carries a fairly high volume. Linden Avenue, on the other hand, is generally uncontrolled and carries a smaller volume in the vicinity of its intersection with Fifth.

The intersection of Fifth and Linden was uncontrolled prior to the beginning of the study. However, local drivers considered Linden to have priority. Figure 34 shows a similar orientation of gap and lag acceptance curves in the middle range of headways (5 to 8 sec) for YIELD control. The two intersections showing the highest acceptance rate are those which also show the highest rate of disobedience to the maximum legal speed of 20 mph through the YIELD sign. In each case the volumes controlled on the minor street exceeded the volumes on the major street. The two lowest curves, on the other hand, have major streets which are generally protected. Kostner has about four to six times as much traffic as Kirk, and the volume on Greenleaf is about equal to that on Fifth. The middle curve is for the intersection of Fifth and Linden. Linden Avenue, as previously discussed, is generally uncontrolled.

Considering the two extreme curves, therefore, the highest is at an intersection whose minor street is given priority at other intersections but is controlled at this one. It has generally good sight distance. The lowest curve, on the other hand, is at an intersection where the major and minor-street traffic are about equal and the major street is protected in the vicinity of the intersection. Parked vehicles restrict sight distance on the minor street.

The general pattern is that the driver's gap acceptance characteristics varied with the way he thought the intersection should be driven. That is, if he believed he should have the right-of-way, he was bolder, but if he was used to thinking of the cross street as dominant he was more willing to yield. To the extent that sight distance was restricted he was even more cautious when faced with a decision on whether or not to accept a gap or lag.

Further review of Figure 34 shows some more detailed possibilities of further interest concerning the effect of sight distance. In the lower range of headways Kirk and Kostner, with adequate sight distance, continues to show an effective advantage with YIELD control. Fifth and Linden, with limited sight distance, does not show this advantage, but rather quickly drops to zero acceptance. Fifth and Greenleaf shows acceptance below all the curves for gaps and lags greater than 4 sec. Below 4 sec acceptance remains below that for Kirk and Kostner. As previously stated, it was noted while conducting field studies that although no permanent physical features limit the sight distance greatly at this intersection, parking on the east leg had a great effect. This was caused by a slight down grade on Greenleaf going eastbound from Fifth. All-day parkers, using nearby rapid transit facilities, parked on both legs of Greenleaf very close to the corner. When a vehicle approached on either leg of Fifth, it was very difficult to see vehicles approaching from the east. There was also some restriction to sight distance on the west due to the parking. In reality, therefore, the sight distance was greatly restricted. This tends to explain the low acceptance curve at this intersection.

Figures 35 and 36 give further information on the characteristics at individual sites. These two figures, comparing gap and lag acceptance for YIELD and STOP control at the two intersections where the control change was made, show the general trend toward higher acceptance at YIELD control. The possible effect of limited sight distance on YIELD control operation occurs at Fifth and Linden (Fig. 35) at gaps and lags below 4 sec.

This discussion suggests that several important factors may have to be considered separately when measuring gap and lag acceptance. Unless the data are stratified to separate these effects, an accurate picture of the acceptance phenomena may not be obtained. This reasoning is based on data somewhat limited in scope and sample size, but it does indicate that further study of these effects is warranted.

A preliminary investigation was made into a method for determining if variation of major-street volumes and major-street speeds affected gap and lag acceptance. This was carried out by combining the results of the computer program on gap and lag acceptance with the program on speed, volume and delay (see Appendix B). This resulted in the data shown in Figures 37 to 40. The gap and lag acceptance characteristics for each minor-street vehicle were correlated with the following information:

1. The 10-min minor-street volume centered around the arrival of the minor-street vehicle at the control.
2. The average speed of major-street vehicles across the intersection for the same 10-min period.
3. The 5-min major-street volume centered around the arrival of the minor-street vehicle at the control.
4. The average speed of major-street vehicles across the intersection for the same 5-min period.
5. The major-street volume during the observance period of the minor-street vehicle.
6. The average speed of the major-street vehicles across the intersection for the observance period.

As defined in a previous section, the observance period is the interval from the time the minor-street vehicle

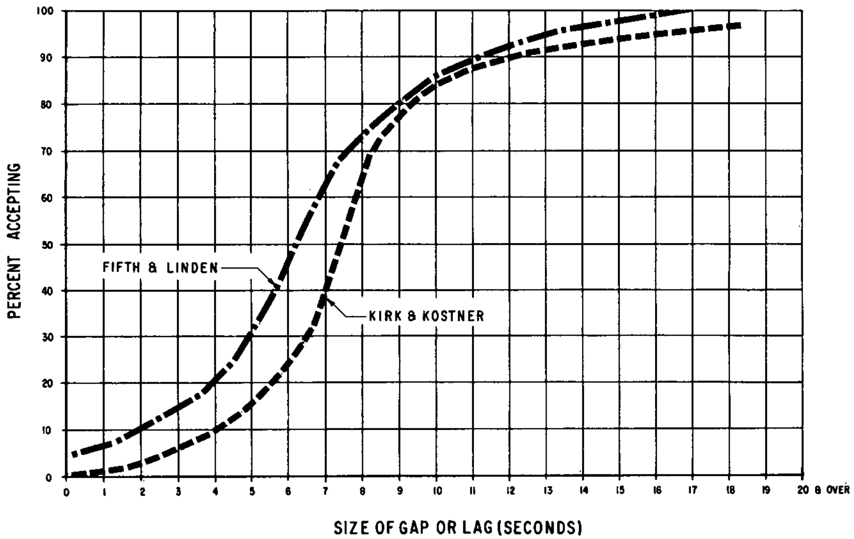


Figure 33. Gap and lag acceptance, STOP *control, combined peak and off-peak periods, Kirk and Kostner vs Fifth and Linden.*

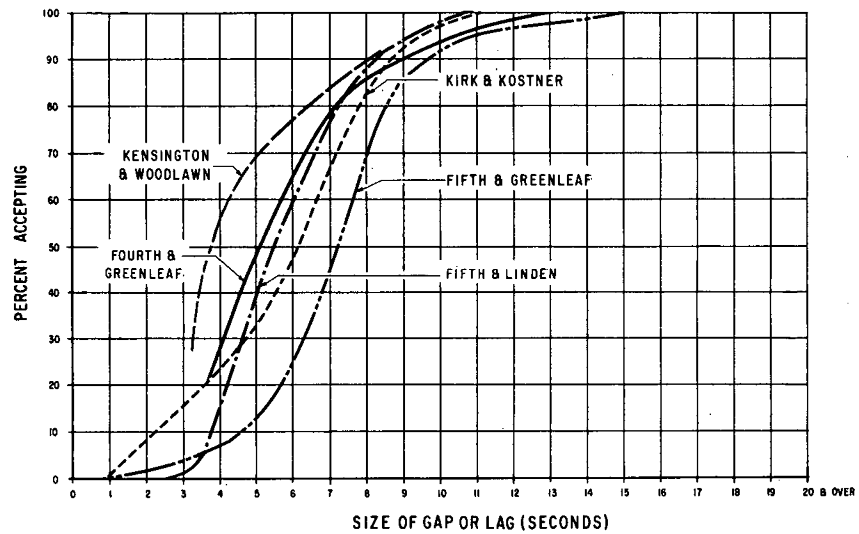


Figure 34. Gap and lag acceptance, YIELD *control, combined peak and off-peak periods, individual study intersections.*

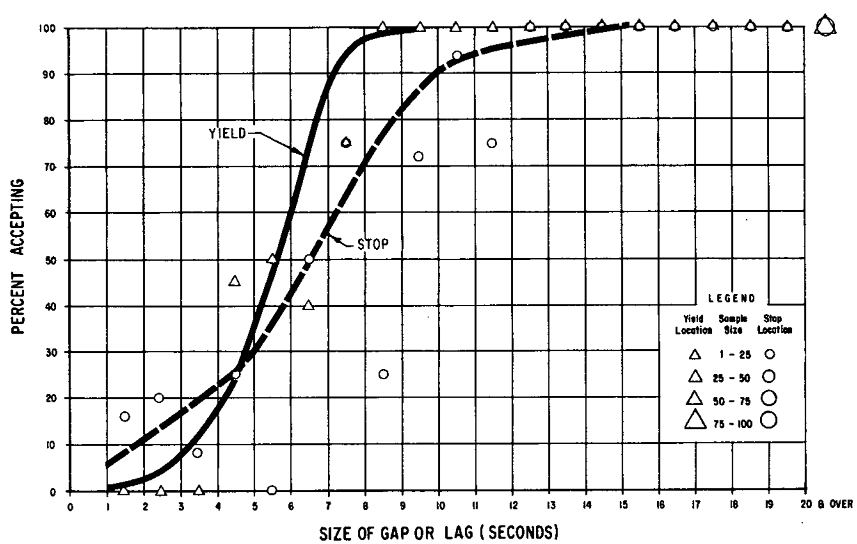


Figure 35. Gap and lag acceptance, YIELD *vs* STOP, *combined peak and off-peak periods, Fifth and Linden.*

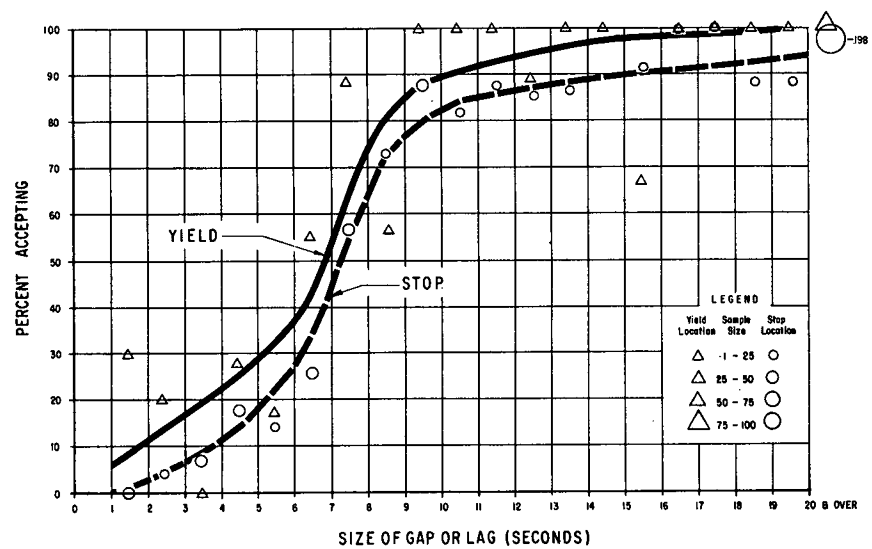


Figure 36. Gap and lag acceptance, YIELD *vs* STOP, *combined peak and off-peak periods, Kirk and Kostner.*

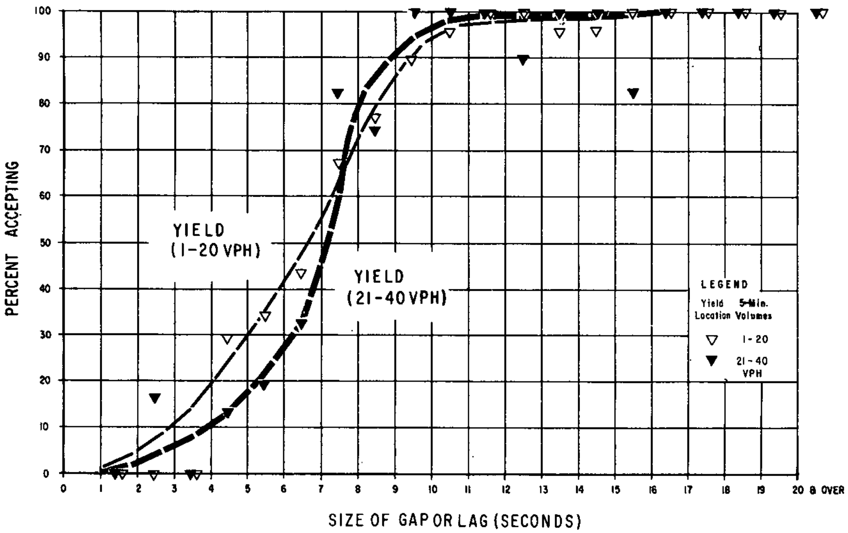


Figure 37. Effect of major-street volume on gap and lag acceptance, YIELD *control, combined peak and off-peak periods.*

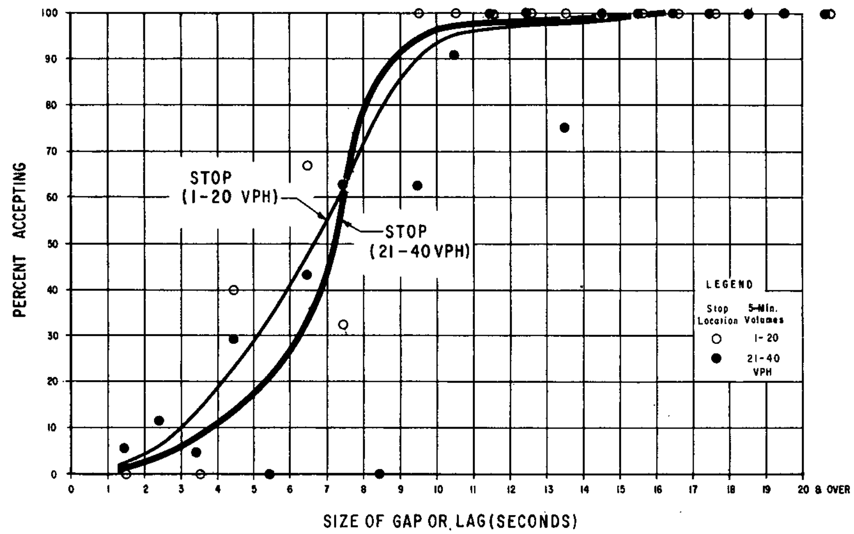


Figure 38. Effect of major-street volume on gap and lag acceptance, STOP *control, combined peak and off-peak periods.*

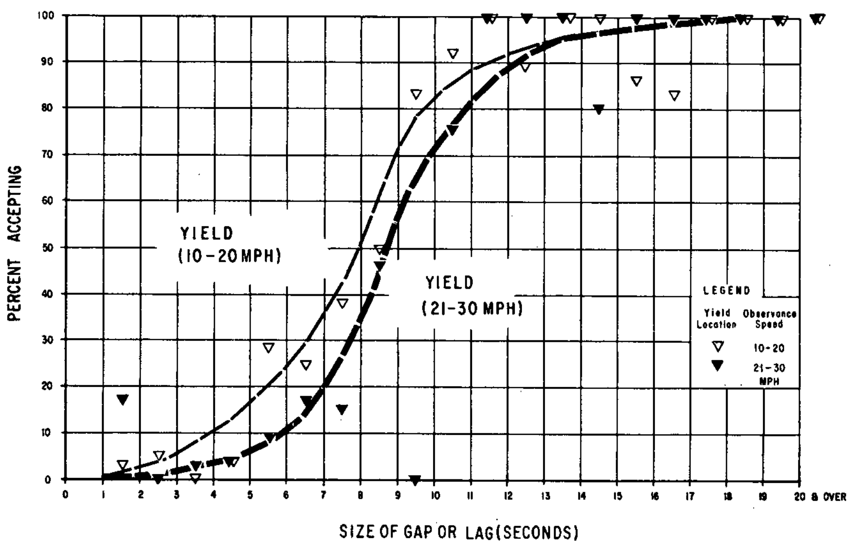


Figure 39. Effect of major-street speed on gap and lag acceptance, YIELD *control, combined peak and off-peak periods.*

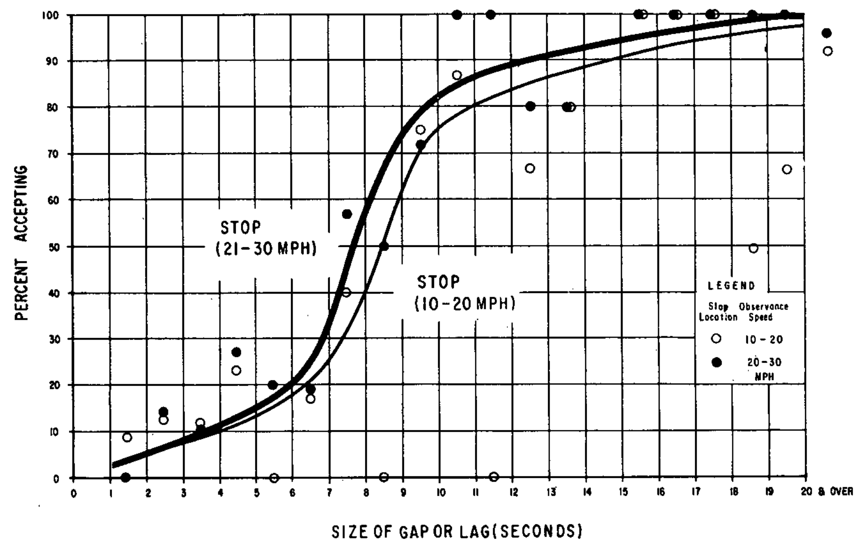


Figure 40. Effect of major-street speed on gap and lag acceptance, STOP *control, combined peak and off-peak periods.*

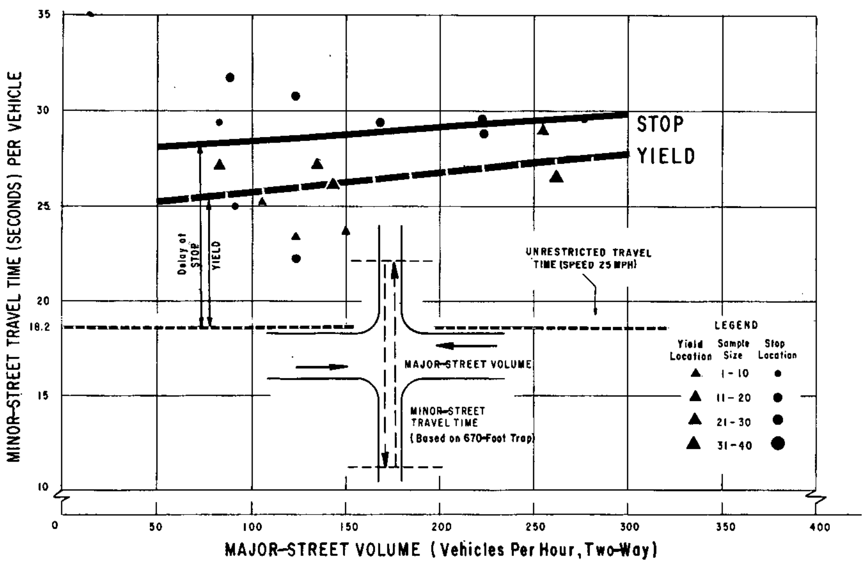


Figure 41. Average minor-street travel time by major-street volume, Fifth and Linden.

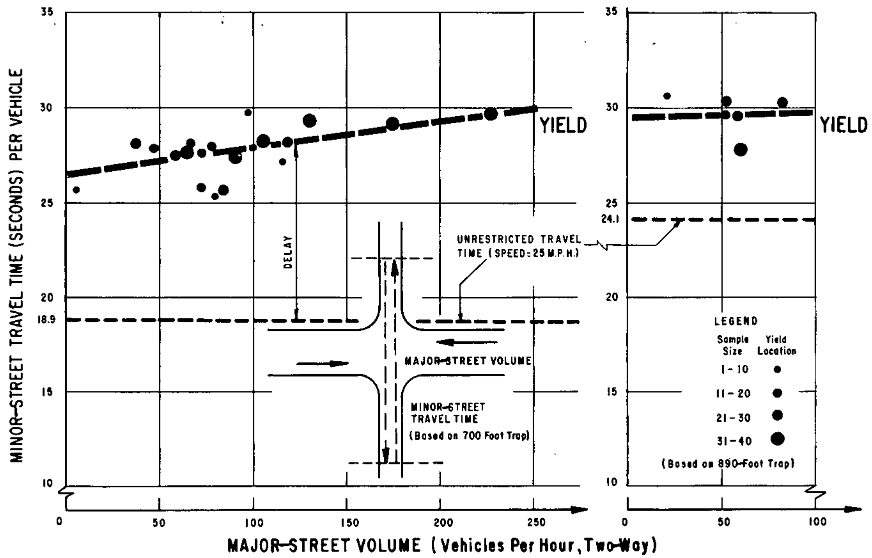


Figure 42. Average minor-street travel time by major-street volume, Fifth and Greenleaf (left) and Kensington and Woodlawn (right).

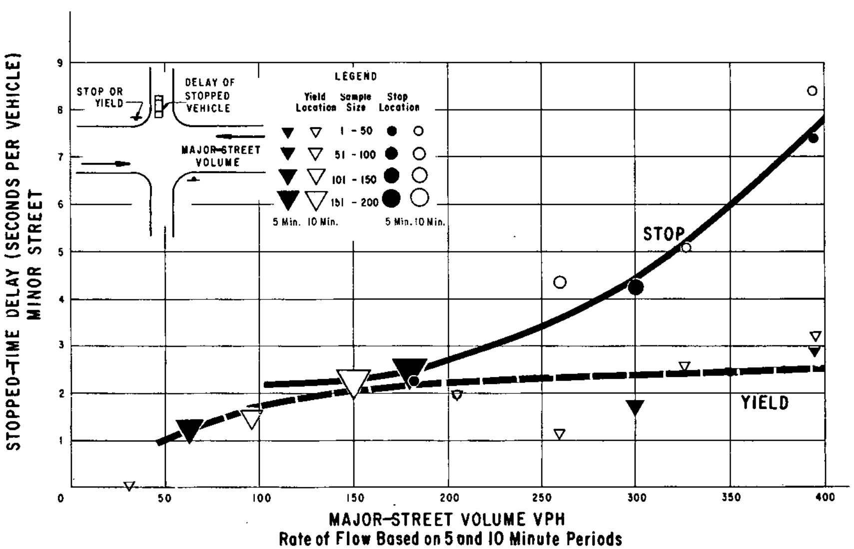


Figure 43. Average minor-street stopped-time delay by major-street volume, all intersections.

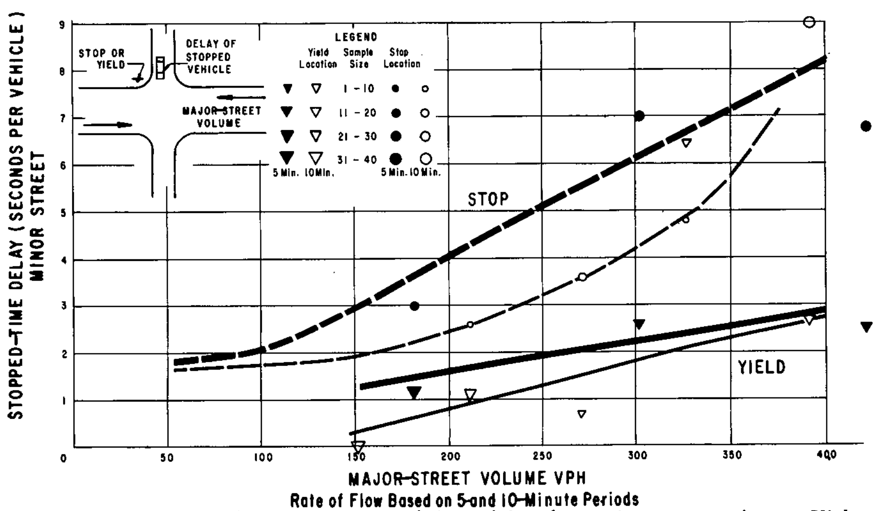


Figure 44. Average minor-street stopped-time delay by major-street volume, Kirk and Kostner.

leaves the previous intersection to the time it moves into or across the intersection. It is the period, in other words, during which the driver is able to observe the activity within and around the intersection he is approaching.

It became obvious that the volumes for the observance period are not comparable because of variations in the length of that interval. Investigation of the results revealed that a pattern appeared only for the data using the smallest of the two other intervals. Therefore, Figures 37 and 38 show the results of the volume analysis based on the 5-min period. The sample size, after this type of stratification, was quite limited. This required that volumes be put into two groups—0 to 20 vehicles in 5 min and 20 to 40 vehicles in 5 min.

The variation of volume seems to have an effect on the combined gap and lag acceptance at the YIELD-controlled intersection (Fig. 37). The trend for sizes of 3 to 7 sec shows a lower acceptance at higher volumes. On either side of this range of gap and lag sizes there is no definite pattern to indicate that the YIELD and STOP controls differ. The data on STOP control (Fig. 38) are quite limited in sample size. Although the approximated curves drawn through the points are different for YIELD and STOP control, statistical tests show no significant difference. Furthermore, the points do not follow definite trends that justify preliminary conclusions.

Figures 39 and 40 show the average intersection speed analysis for the observance period. Because of the sample size limitations previously mentioned, speeds were combined in 10-mph groups for 10 to 20 mph and 20 to 30 mph. It must be kept in mind that these curves show combined gap and lag acceptance.

The film data were accurate within 0.6 sec. The traps used for obtaining the intersection speeds varied between approximately 50 and 80 ft. The resulting speed determination decreased in accuracy quite rapidly as actual speeds increased. Further investigations should be based on a more accurate method of speed determination. However, in order to arrive at some preliminary measurement of the speed effect, the speed conditions were grouped as indicated. Inasmuch as there was no tendency for the calculated speeds to cluster about the 20-mph border line between the two groups, it was reasoned that some of the inaccuracy was cancelled in the grouping, thereby giving some credence to the resulting relationship. Here again the results showed a tendency for the YIELD control to be affected over the middle range of gaps and lags. The figures show a definite trend, although not statistically significant, toward lower acceptance for 20- to 30-mph speeds than for 10- to 20-mph speeds. This trend is apparent over the range of sizes from 5 to 13 sec. Above and below this range the curves tend to coincide. The pattern for STOP control is likewise limited by sample size. A general trend is exhibited toward lower acceptance with lower major-street intersection speeds.

Although limited, the results seem to indicate the major-street volume and speed may have some psychological effect on the driver which cause him to adjust his acceptance characteristics at a YIELD sign. It is interesting to note, from the comparison of the individual intersections and the results just discussed, that a major determinant of this hypothesized psychological effect seems to be the general character of the major street.

Travel Time and Delay

Travel times of minor-street vehicles which proceeded through the intersection without turning were analyzed for several of the study intersections. The travel time was taken as the length of time it took to travel from a point prior to the intersection to another point beyond the intersection. The travel times, measured by stopwatch and enoscope, were correlated with their corresponding 5-min major-street volumes. Sample sizes for each 5-min volume group were so small that the data were grouped by hourly volume. Grouping was done by calculating average travel times for each hour. The corresponding volume for that period was taken directly from the manual counts made at the same time. The distance used as a "trap" for measuring travel time varied between intersections. The points at the beginning and end of each "trap" were chosen by inspection of the speed profiles. An attempt was made to begin and end the measurement at the point of maximum vehicle speed. This approximately coincided with the point of placement of the third enoscope from the intersection as used to obtain the speed profiles.

Figure 41 compares travel times for through vehicles on the minor street at Fifth and Linden under YIELD control and STOP control. The distance over which this time was taken was 670 ft. The travel times are plotted against major-street volume. The highest major-street volumes recorded here were approximately 275 vph. The approximated curves indicate that there is generally a decrease in travel time of about 2 to 3 sec under YIELD control at the volumes studied. There is an indication that the difference in travel time increases at major-street volumes below 150 vph and that there is a slightly greater difference in travel time between YIELD and STOP control at lower volumes than at higher volumes. The general increase is about 1 sec per 100 vph on the major-street for volumes of up to about 300 vph. Larger volumes were not studied. Hypothetically, at lower volume levels a vehicle at a YIELD control will continue through, without stopping, at some minimum travel time, but at a STOP control it will take longer due to the requirement to stop before proceeding into the intersection.

Defining delay, using travel time as a measure, requires a number of assumptions as to how the driver would cover the same distance if there were no cross street. This "unrestricted time" can then be subtracted from actual travel time to estimate delay. The resulting quantity includes deceleration and acceleration delay, as well as stopped-time delay. A number of methods and assumptions have been used. However, the mere fact that such a variety exists indicates the difficulty of obtaining "absolute" delay. One major assumption is that the initial approach speed to the intersection represents the average unrestricted speed if there were no intersection. Calculation of the unrestricted time for the through vehicle is directly depend-

ent on this assumption. It was decided, therefore, not to estimate a fictitious speed by interpolating a value from the speed profiles. Instead, it was deemed sufficient for the purposes of this stage of research to calculate the delay based on the prevailing maximum legal speed. The speed of approach, therefore, was taken to be the speed limit. In effect, this assumes that if the intersection had not been there, the driver would have passed through the entire travel time "trap" at the speed limit.

The unrestricted travel time at Fifth and Linden, corresponding to the speed limit of 25 mph for a distance of 670 ft across the intersection, is 18.2 sec for vehicles proceeding straight through. This has been plotted as a horizontal line on Figure 41. Therefore, the distance between this line and the travel time for each control, in seconds, is the estimated average maximum delay which can be attributed to this intersection, predicated on the maximum legal speed and the measured travel times at each volume within the range studied. Between major-street volumes of 150 to 300 vph the difference in delay between the YIELD and STOP controls approaches a value of approximately 2.0 sec. For the example used here, predicated on an unrestricted speed of 25 mph, the average delay indicated is about 9 sec for YIELD and 11 sec for STOP control for a major-street volume of 300 vph. In this case the delay was based on a legal speed limit; but actually any other horizontal line could be inserted to meet the desired assumptions for other analyses. However, the difference in delay between the two controls would remain unchanged.

Figure 42 shows the travel times for vehicles proceeding straight through on the minor street at the YIELD-controlled intersections of Fifth and Greenleaf, and Kensington and Woodlawn. None of these travel times can be compared directly between intersections as the length over which they were taken differed from one intersection to the other. However, the delays at each intersection can be compared, as discussed in the following.

It is apparent that there was not enough volume variation at Kensington and Woodlawn to estimate the effect of major-street volume on minor-street travel time. Comparison of the points with the unrestricted travel time line shows a variation in average delay between 4 and 6 sec over a major-street volume between 25 vph and approximately 80 vph.

Travel times were obtained at Fifth and Greenleaf over a major-street volume range between 15 and 225 vph. The approximated line tends to rise a total of about 3.5 sec over the range. The unrestricted travel time line shows a variation of delay between 7 sec and 11 sec at projected volumes of 0 and 250 vph.

Travel time and delay information for Kirk and Kostner were studied in detail by Radelat.* The results of those investigations are discussed in Chapter Five.

Comparison of the intersections under YIELD control reveals that the delay at Fifth and Greenleaf was greater than at the other two intersections for the comparable volumes studied. No comparison is possible between Fifth and Linden and Kensington and Woodlawn because there was no overlap of the volume ranges studied.

Stopped-Time Delay

Figures 43 and 44 show the results of a study of stopped-time delay. The information was obtained from film analysis. The data used were the output of the computer program for speed, volume and delay. Stopped-time delays for all intersections were averaged for type of control and grouped by volume. Major-street volumes based on both 5- and 10-min rates of flow were investigated. Little difference was found between the two for the combined results. These were grouped by ten vehicles for the 5-min period and expanded to an hourly rate of flow. Figure 43 shows that with a major-street volume above 200 vph the stopped-time delay increases rapidly at a STOP sign whereas at the YIELD control the stopped-time delay increases very little. Over the range of volumes from 175 vph to about 425 vph the STOP control stopped-time delay increases from about 2 sec to about 8 sec. In the same range, stopped-time delay under YIELD control increases from about 2 sec to 3 sec.

Statistical tests, performed to determine significance of difference of stopped-time delay for YIELD control and for STOP control, respectively, for each volume group show that for the volumes at which the curves diverged, the differences are significant.

The operation at lower volumes can be hypothesized. As the major-street volume approached zero the major-street interference would become negligible and stopped-time delay under STOP control would fall to some constant, non-zero level. Under YIELD control the stopped-time delay should approach zero. This would indicate that there would be some major-street volume level at which the stopped-time delay under each control would reach some minimum difference (it is likely that STOP control will always have at least a slightly higher stopped delay). On either side of this point of minimum difference the difference would increase or stay equal, but never decrease, and the stopped-time delay for YIELD control would always remain less. Stopped delay per vehicle would probably approach the same value for YIELD and STOP control at some major-street volume much higher than those studied.

The same information is shown in Figure 44 for the intersection of Kirk and Kostner alone. Here separate curves are indicated for both a rate of flow based on a 5-min period and on a 10-min period in order to show what differences occur. It is reasoned that the 5-min rate of flow should be a more sensitive indicator because it more accurately describes the major-street flow faced by the vehicle when passing through the intersection. Relations based on other periods of rate of flow, including a full hour, should be investigated.

Percent Stopped

As a by-product of the investigation of driver obedience (to be discussed later) some information was obtained on the percent of vehicles forced to slow or stop by traffic. These data reveal that at Fifth and Linden the percent

* Radelat, *Ibid.*

stopped by traffic increased by about 8 percent in the peak period and 7 percent in the off-peak period after YIELD control was replaced by STOP control. A similar increase occurred during the peak period when the intersection control was changed from uncontrolled to YIELD control. However, no effective change occurred during the off-peak period.

A change in control from YIELD to STOP at Kirk and Kostner caused an increase in forced stops of 13 percent in the peak period and 6 percent in the off-peak period. These results further indicate the advantage that the driver has at a YIELD-controlled intersection of the type studied here. It shows that the increased freedom of the driver to move through the intersection decreases his delay.

Speed of Operation

The results of the data gathered for speed profiles on both the major and minor streets are shown in Figures 45 to 48 for each study intersection. The values were obtained by averaging speeds across each "trap" (locations shown in Figs. 5 through 11).

Statistical tests were performed to determine the significance of the differences obtained for speeds at the intersections where controls were changed. The results of these studies are discussed in the following.

Figure 45 shows the speed profiles for through vehicles on all four legs of the intersection of Fifth and Linden for each of the three control conditions studied. The points do not differ significantly in general. The profiles for the southbound approaches on the minor street indicate that uncontrolled and YIELD-controlled vehicles tend to approach at higher speeds than STOP-controlled vehicles. In general, as the control becomes more restrictive the speed decreases in the last trap before the control decreases. On the northbound approach, however, the vehicles tend to follow the same speed pattern regardless of control. The speed in the trap closest to the intersection is about 3 mph lower than the southbound approach. These characteristics are probably due to the slightly greater sight restriction on the northbound approach. As the intersection control becomes more restrictive, the speeds of vehicles just leaving the intersection and proceeding northbound tend to decrease. However, this trend does not occur for southbound traffic. This difference is not easily explained with the data available.

Speeds seldom varied under different controls by more than 2 to 3 mph in any one trap. Speeds recorded never averaged below 15 mph within the section of roadway studied. This, plus some of the unexplainable patterns that occurred, seems to indicate that a more detailed study of deceleration and acceleration of minor-street vehicles is warranted over the section from just prior to, to just beyond the intersection.

On Linden Avenue, the major street, there was a tendency for westbound vehicles to approach at the same speed under all control conditions. As they departed there was an average speed drop of about 3 mph with the uncontrolled condition, which did not occur with positive side-street controls. However, eastbound traffic used lower approach speeds with YIELD control on the side street than with STOP control.

If further study with larger samples continues to show the differences in approach speeds to be statistically insignificant, the conclusion could be drawn that the type of control has no effect on speeds of vehicles about 100 ft ahead of the control.

General review of the shapes of the profiles indicates that the driver begins to decelerate on Fifth (minor street) about 200 ft ahead of the control and regains his normal speed approximately 200 ft beyond the control. This varied somewhat between types of control. In general, the YIELD-controlled vehicle began decelerating at about the same point or somewhat closer to the control than the STOP-controlled vehicle. Sight distance seems to be an important factor.

Speed profiles for through vehicles at Kirk and Kostner are shown in Figure 47. More information concerning this intersection is discussed in Chapter Five. The data available on the minor street allow comparison of YIELD and STOP control on the westbound approach only. Statistical tests show no general significant differences. There seems to be no difference in trends of the curves, except that the profile for STOP control is erratic. The profiles for the major street also show little difference in operation except for the northbound traffic leaving the intersection. This is probably due to the change from four-way STOP to signal control at Oakton and Kostner between the times that speeds were taken for YIELD control and STOP control at Kirk and Kostner. The profile for four-way STOP control at Oakton and Kostner would probably have shown lower speeds for the northbound vehicles leaving Kirk and Kostner.

Several items can be noted from the general shapes of the curves in Figure 47. First, the profiles indicate a drop in major-street speed across the intersection for each minor-street control condition. The decrease for each control is about the same, although the last point on each approach shows a slightly lower speed under YIELD control. Second, the point at which southbound vehicles begin to decelerate is about 210 ft ahead of the intersection. The maximum speed is reached about 200 to 250 ft beyond the intersection. This is true for both control conditions. The northbound pattern differs with each control condition. However, this has been attributed to the control change at Oakton and Kostner, so direct comparison is not warranted. On the minor street the westbound vehicles approaching the control start to decelerate as soon as they pass the previous intersection (which is uncontrolled and about 350 ft away). Eastbound vehicles begin deceleration about 125 ft ahead of the STOP control. The maximum speed of vehicles leaving on the minor street legs is reached about 100 to 125 ft beyond the intersection.

Figure 46 shows the speed profiles for the intersection of Fifth and Greenleaf under YIELD control. The profiles for the minor street have the same general shape for the northbound minor-street vehicle at Fifth and Linden under YIELD control. The major-street profiles show a slight dip in speed across the intersection for eastbound vehicles. Westbound vehicles accelerate continuously from the pre-

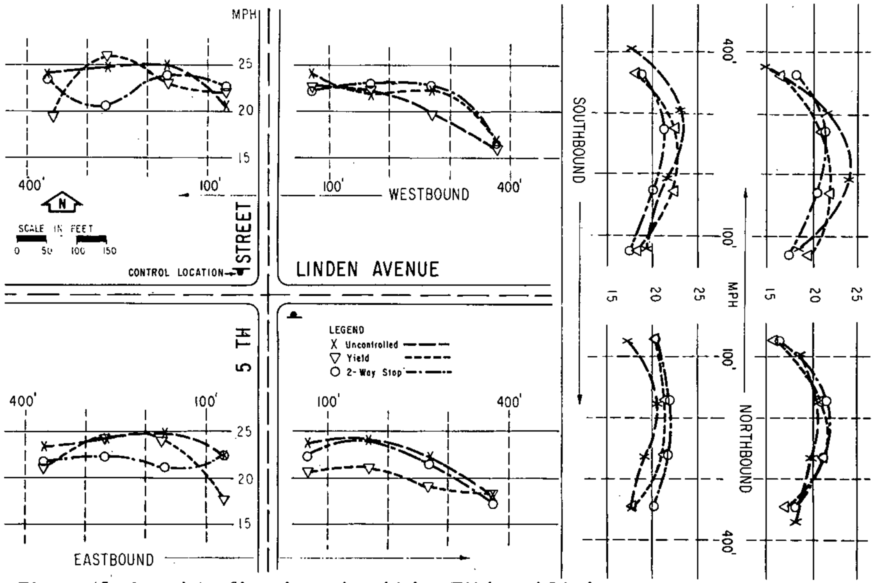


Figure 45. Speed profiles, through vehicles, Fifth and Linden.

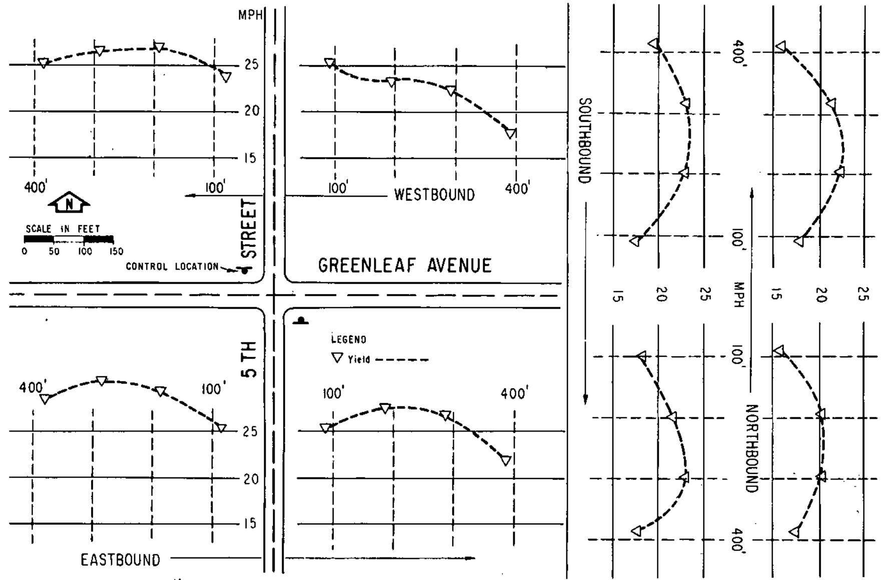


Figure 46. Speed profiles, through vehicles, Fifth and Greenleaf.

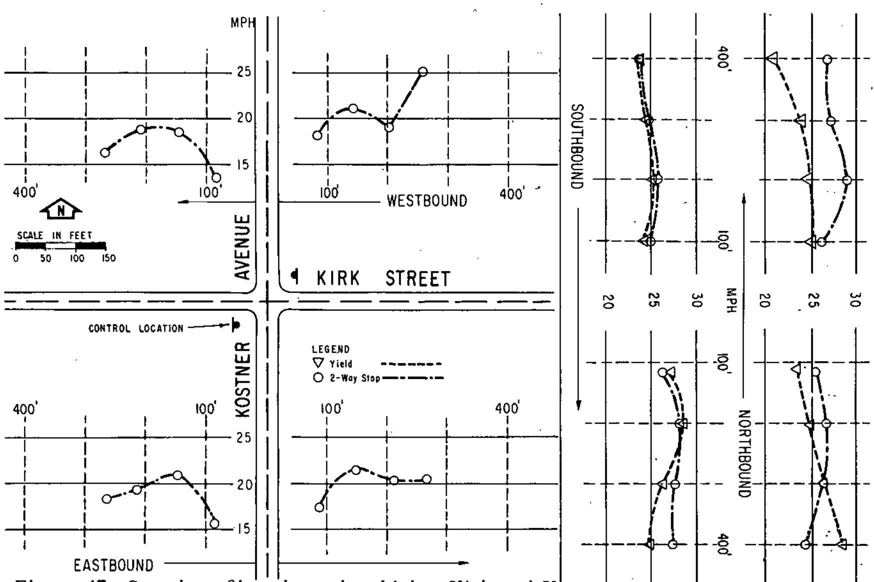


Figure 47. Speed profiles, through vehicles, Kirk and Kostner.

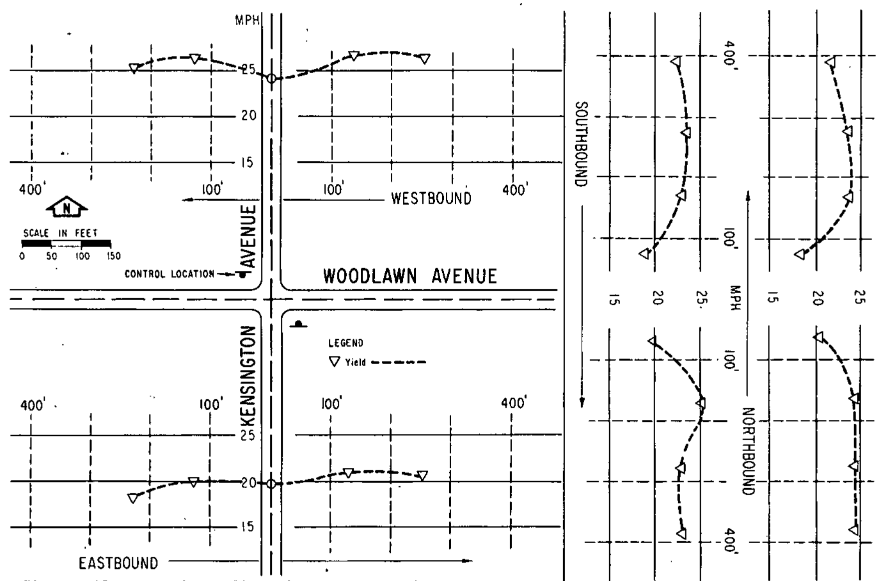


Figure 48. Speed profiles, through vehicles, Kensington and Woodlawn.

vious intersection to the beginning of the study intersection. The drop in average speed on the other side of the intersection indicates that there has been some slowing across the intersection. The continuous acceleration is due to the fact that the majority of westbound vehicles have turned left from Fourth Street and have proceeded along Greenleaf, leveling off in speed as the maximum of about 27 or 28 mph is reached. Figure 46 indicates that the deceleration and maximum speed points are all located at approximately 200 to 225 ft from the intersection.

Figure 48 shows speed profiles for vehicles proceeding straight through at Kensington and Woodlawn under YIELD control. The deceleration and acceleration of minor-street vehicles are generally as found for the other study intersections. However, the profiles are flatter prior to the beginning of deceleration. This can be attributed in general to the greater distance between intersections here than at the other study sites. Furthermore, although Kensington is the controlled street at Woodlawn, it is the preferential route at intersections on either side of the study site. The deceleration and maximum speed points are generally 275 ft from the intersection. The profiles for through vehicles on the major street, taken continuously across the intersection because of the short distance to the adjacent intersections on Woodlawn (about 200 ft), show only a very slight dip in speed across the intersection. Otherwise the speeds measured were fairly constant across the section being measured.

Figure 49 shows the results of a study of turning and through vehicles at the intersection of Fifth and Linden. The approaches on the minor street are shown for each control condition studied. It is interesting to note that on the northbound approach the speed profiles of the turning and through vehicles are quite similar, whereas on the southbound approach some variation occurs under certain control conditions. This is probably a result of the somewhat greater sight restriction to the east for northbound approaching drivers. The southbound approach shows that for uncontrolled conditions there is a difference between speeds of turning and through vehicles. However, as the control becomes more restrictive the differences tend to disappear. It should also be noted that for YIELD control and STOP control the last measured speed prior to the intersection is generally lower for the southbound approach than under corresponding control for the northbound approach. This is not true for the uncontrolled condition.

Headway Distribution

Headways were computed from the intersection film data for two particular types of investigation: (a) the study of headways of arrival as affected by the control at the previous intersection; and (b) the study of the redistribution of headways of minor-street vehicles which resulted from passage through the control. Details on the method are given in Appendix A.

In reviewing the results presented and discussed in the following, several things should be kept in mind. First, the study of headways of arrival put out from a control at a previous intersection are measured one block away from the intersection. Thus, the possibility of rearrangement of headways on the midblock length (which varied between about 300 and 600 ft) of roadway could easily affect the resulting arrival rates. Second, this preliminary investigation did not attempt to determine the effect of crossing volume at the previous intersection which was interfering with the stream being measured. The crossing (interference) volumes at the previous intersections range between 25 and 900 vph. The magnitude of the crossing volume generally related to the level of control at the previous intersection. The stream volumes measured range between approximately 25 and 300 vph. The two-way major-street volumes considered in connection with changes in headways between arrival and departure at the study intersection vary between 50 and 400 vph. The turning movements at all but one or two cases were light.

Headways were measured at the arrival line on each leg at each of the study intersections. The distance from the control to these lines varied according to the field of view allowed by the camera. The average distance was approximately 75 ft ahead of the control, the point always being set back as far as possible to minimize the effect of the intersection. It is recognized that the travel on the length of roadway between intersections may have slightly transformed headways, because all vehicles do not travel at the same speed. The distances between the study intersections and their adjacent intersections varied from 300 to 500 ft.

The measured streams were combined by 50-vph volume groups over the range between 0 and 300 vph. The controls at the previous intersections include YIELD, two-way STOP, four-way STOP, no control, and those which were "protected by YIELD or STOP." The headways were summarized in 1-sec increments from 0 to 20 sec, and 10-sec increments from 20 to 100 sec.

Two series of diagrams were made: (a) a graph for each volume group showing the number of headways for each increment as the percentage of all recorded headways for a given previous control (Figs. 50 to 57); and (b) a graph for each previous control showing the cumulative percentages of all recorded headways, compared with the exponential distribution of an undisturbed traffic flow having the same average volume (Figs. 58 to 62).

Figures 50 to 54 were studied to determine the effect that the control of the previous intersection had on the arrival rate at the study intersection. A further study was made to determine whether the arrival rates could be closely approximated by a theoretical distribution.

Statistical calculations were made to determine differences between the headway distributions measured from each "previous" control. The results of these tests are given in Appendix B. Where significance occurs between two controls at the 95 percent level of confidence it is indicated on the figures with a solid arrow between the two points. A similar "dashed" arrow is shown where significance occurs at the 90 percent level of confidence.

There are very few cases of significance above 90 percent confidence. The few cases that do appear do not follow any pattern. The accuracy of this comparison is limited by the grouping. Because of the 50-vph grouping,

it is likely that the average stream volumes being compared between two different controls might be somewhat different. This is treated in more detail later in this section.

The study of the type of distribution obtained revealed that the measured headways vary in such a manner that, on the average, they closely approximate the average expected curve derived from the undisturbed Poisson distribution, which assumes that the vehicles arrive in a random manner.

The percentages for the theoretical curve (according to the exponential function derived from the Poisson distribution for undisturbed flow) were calculated for the median volume of the range being considered. For example, 75 vph was used for the range of 50 to 100 vph. The curves resulting from these calculations are shown on the figure with the corresponding volume group. The percentages decrease slightly with increasing size of headway.

The formula for the exponential distribution follows the form

$$P=\exp\left(-\frac{t-S}{T-S}\right)\times\left[\exp\left(\frac{1}{T-S}\right)-1\right]100\% \qquad (1)$$

in which

P=percent of headways with size between t and $t-1$ sec;
t=headway size (abscissa in the figures);
T=average headway size (3,600/V);
S=minimum headway (1.5 sec); and
V=volume, in veh per hr.

It can be seen that the measured headways vary in such a manner that, on the average, they closely approximate the average expected theoretical curve derived.

The cause of the variation in distribution of arrival headways (Figs. 50 to 54) was investigated. It was first suggested that it might be due to the relatively small sample size for each type of previous control. In order to increase the sample size, all counted headways were summarized over all volumes and controls. In the overall total histogram (Fig. 55) the magnitude of oscillation about the exponential curve has been reduced somewhat. Further study showed that a major portion of the alternating high and low percentages were due to the particular method of grouping used. The headways were summarized by 1-sec increments, whereas the film allows measurement from the frames only in multiples of 0.6 sec. Therefore, some 1-sec increments include two multiples of 0.6, and others only one.

As an example of how this would smooth out, the values for each previous control were computed by 0.6-sec increments for the volume groups of 100 to 150 vph. Time variation continued to be present because of the small sample available. The values grouped for all controls and based on 20 films (Fig. 56) show a relatively smooth fit to the corresponding exponential curve.

To increase sample size even further, an additional smoothing was carried out on this particular volume grouping by averaging successive 3-sec headway size groups. The resulting curve and the corresponding exponential (Fig. 57) have a marked decrease in variation, showing quite a close approximation to the theoretical distribution.

A further explanation of variation arises when considering the assumption used in applying the undisturbed distribution. Inspection of the plotted points shows the variation about the exponential to be larger at smaller headway sizes than at the larger ones. This is probably due to the intra-stream vehicle friction at small headways which is not present at large headways (above about 9 sec).

The second series of diagrams (Figs. 58-62) was also analyzed in an attempt to determine the effect of previous control on headways of arrival, and to evaluate the distribution. In each case, the headways of arrival for one type of previous control, plotted as the cumulative percentage of headways for each stream volume group, are shown in 1-sec increments up to 20 sec and in 10-sec increments between 20 and 100 sec.

Each of the cumulative curves is compared with a corresponding cumulative distribution. It should be noted that the headways of arrival of several intersection legs having the same previous control and the same volume range were combined to produce each curve. The average volume represented by each curve is not exactly the median value of the volume range. The average was calculated, however, and used to compute the exponential distribution. The exponential distribution based on Poisson's law is used for these relatively low volumes in its simple form, and not modified to include the assumption of the presence of non-free-flowing vehicles. On the other hand, it takes into account a minimum headway, which was estimated to be 1.5 sec. The form of the equation is

$$P'=\exp\left(-\frac{t-S}{T-S}\right)100\% \qquad (2)$$

in which P' is the probability, in percent, of occurrence of headways of t seconds or greater, and the other terms are as previously defined. The complementary form for finding headways of a given size or less is

$$P''=100-P' \qquad (3)$$

The exponential curves at the different volume levels start at zero percent for the minimum headway of 1.5 sec, and increase toward 100 percent faster with progressively higher stream volumes. The break between 20 and 30 sec is due only to a change of scale.

Generally the distribution of the measured headways fits the corresponding exponential curve quite well at the same average volume. For the different controls and volumes the following deviations can be noted:

1. YIELD control (Fig. 58)—There seem to be fewer small headways of up to 6 sec but more between 8 and 11 sec at the lower volume (68 vph).
2. Two-way STOP (Fig. 59)—The headway accumulation lies slightly above the theoretical curve.
3. Four-way STOP (Fig. 60)—At the highest measured volume (216 vph) there are fewer headways smaller than 3 sec than expected, but a greater number fall between 3 and 5 sec. This keeps the accumulation curve above the theoretical distribution.
4. No control (Fig. 61)—At the highest measured volume (117 vph) the headways up to 5 sec seem to be more

numerous than expected, keeping the accumulation above the theoretical curve until sizes of about 15 sec or greater are reached.

5. Protected by YIELD or STOP (Fig. 62)—When the measured stream has priority, there seem to be more small headways of 2 to 3 sec than the exponential distribution would predict for volumes of less than about 100 vph. For a stream volume of approximately 200 vph, however, the study shows a close fit to the exponential curve. The numerous small headways at the lower volumes (33 and 74 vph) are presumably due to platooning of vehicles. This means that for these stream volumes more vehicles tend to arrive at the minimum headway if the previous intersection is protected. This effect is probably even more evident with signals at the previous intersection. However, no usable measurements were taken for this study.

Recalling the conditions pointed out at the beginning of this section, two characteristics are evident: (a) when the flow at the previous intersection is "protected" by either YIELD or STOP control, there is a tendency in the undisturbed traffic stream to form platoons; and (b) when the traffic stream passes through YIELD or STOP control at the previous intersection, the interruption of the control and the crossing (interference) volume tends to spread out the vehicles proceeding at very close headways.

These statements lead to the further conclusion that intersections farther away in the system, especially those controlled by signals, have an important effect on headway arrivals. The extent to which these other intersections act to control arrivals would be an interesting subject for later study.

These results indicate that the exponential distribution, with a minimum headway of 1.5 sec, closely describes the distribution of headways of arrival from previous YIELD- and STOP-controlled intersections. If further study supports this finding, it can be of great use in simulation studies of intersections.

The second major investigation of headway distributions, comparing headways of arrival and departure headways, was actually conducted as an alternative method to that just discussed. The objective in each case was to determine how a control at one intersection affects the arrival of vehicles at adjacent intersections.

The study of headways of arrival and departure was made at each study intersection for pairs of through vehicles on the minor street only. A study was made of individual headway changes and of headways grouped by size to form a distribution. These changes were correlated with the major-street volume to determine the effect that the interference of major-street traffic had on vehicle spacings on the minor street before and after the intersection.

Figures 63 and 64 show the change of individual headways on the minor street for YIELD and STOP control for two different major-street volume groupings. The change of each minor-street headway between arrival and departure (immediately before and after the intersection) is shown by a vertical bar located on the abscissa according to the size of the headway upon arrival. This type of figure also shows the number of counted headways and the distribution by arrival size. These particular diagrams further show that the headway increases or decreases generally occur in a random manner, not seemingly a function of headway size.

It is important to note that the average increase and the average decrease in each volume group are of approximately the same magnitude. The average decrease, however, is slightly smaller because there is theoretically no limit to headway increase, but there is a limit to headway decrease. This last rule is obvious, because no headway can be decreased below the minimum headway size of approximately 1.5 sec, indicated by a diagonal line at the left end of the figure.

The average increase and decrease of headways show another characteristic. Within the volume range of 0 to 100 vph on the major street, the STOP sign causes bigger changes of the headway sizes than the YIELD sign (averages of 4.5-sec increase and 4.1-sec decrease at STOP control, compared with 2.65-sec increase and 2.63-sec decrease at YIELD control). The same result occurs for the volume range between 100 to 400 vph on the major street (averages of 6.0-sec increase and 4.7-sec decrease at STOP control, compared with 3.0-sec increase and decrease at YIELD control). Considering the crossing volume, another rule is shown by the average headway changes: The magnitude of the change in headways between straight through vehicles increases or decreases as the crossing volume increases. For YIELD control it is about 2.6 sec for the 0- to 100-vph range and 3 sec for the 100- to 400-vph major-street volume range. For STOP control the changes are 4.5 and 4.1 sec for the 0- to 100-vph range and 6.0 and 4.7 sec for the 100- to 400-vph major-street volume range.

The results of the study of the change of headways in the form of a distribution by size of the headways of arrival or departure are shown in Figures 65 to 69. In this comparison the change is not considered at each headway as was done in the previous discussion, but rather by comparing the general headway distribution in advance of and beyond the intersection. This form of the study of the rearrangement of headways, depending on control and crossing volumes, could have some importance in work dealing with system effects on gap acceptance at an intersection. All counted intersections were grouped by YIELD or STOP control and by crossing volumes of 0 to 100, 100 to 200, and 200 to 400 vph. The headways for each group were summarized in 5-sec increments from 0 to 100 sec. The exhibits show the distribution of headways in each size group as a percent of all headways (including those over 100 sec) separately by arrival and departure.

The percentage itself has little meaning, inasmuch as very different volumes on the minor streets were grouped according to the major-street volume. The comparison of arrival and departure is the major item of importance. There is, however, no conclusive general pattern to the changes: it is likely that the transformation of headways happens at random. This would indicate that the departure headways should be random, which agrees with the

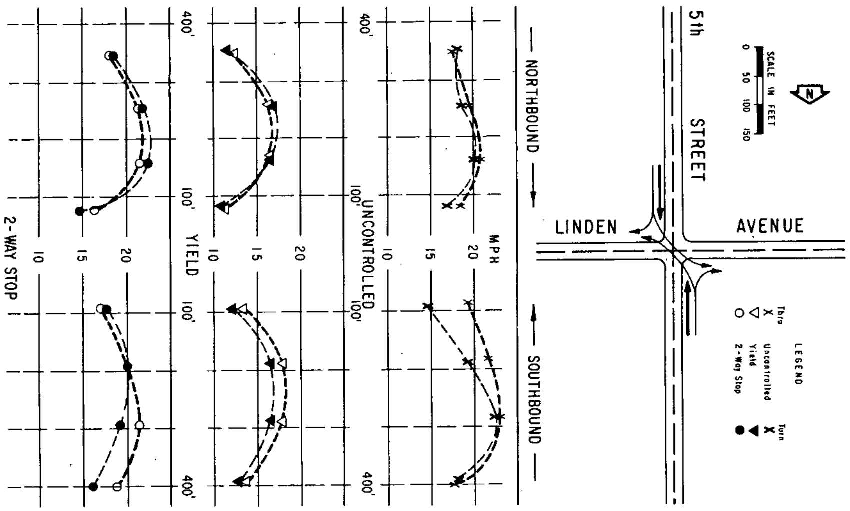


Figure 49. Speed profiles, through and turning vehicles, Fifth and Linden.

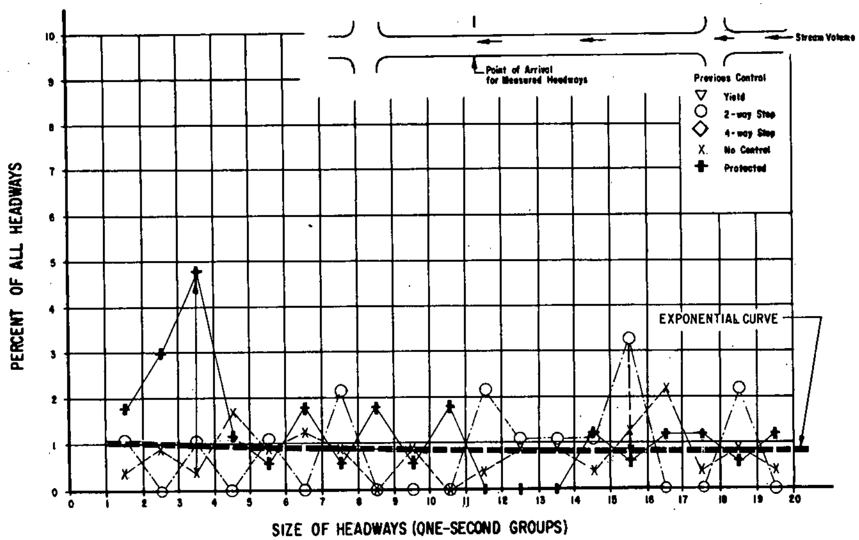


Figure 50. Distribution of headways of arrival, stream volumes of 0 to 50 vph.

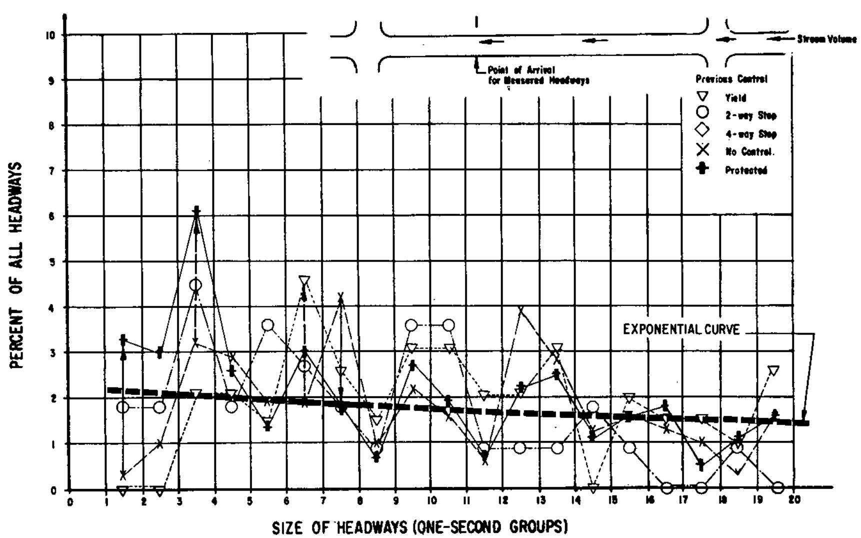


Figure 51. Distribution of headways of arrival, stream volumes of 50 to 100 vph.

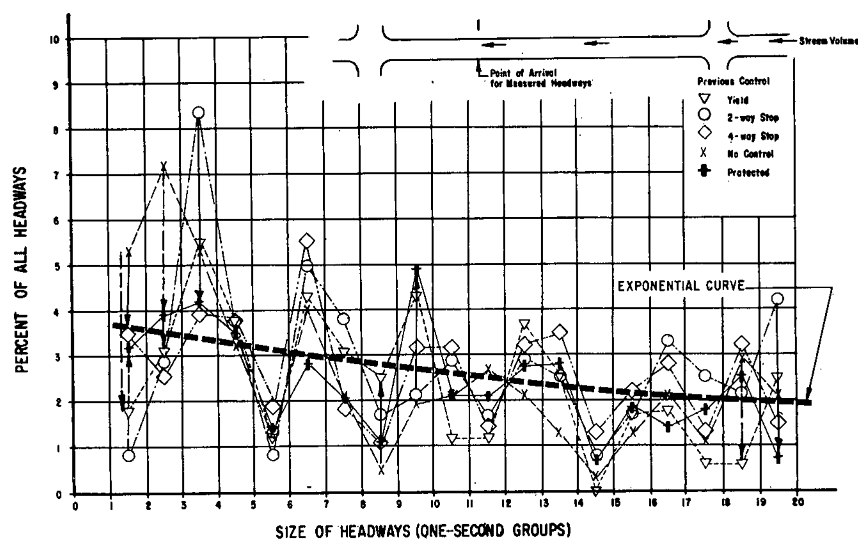


Figure 52. Distribution of headways of arrival, stream volumes of 100 to 150 vph.

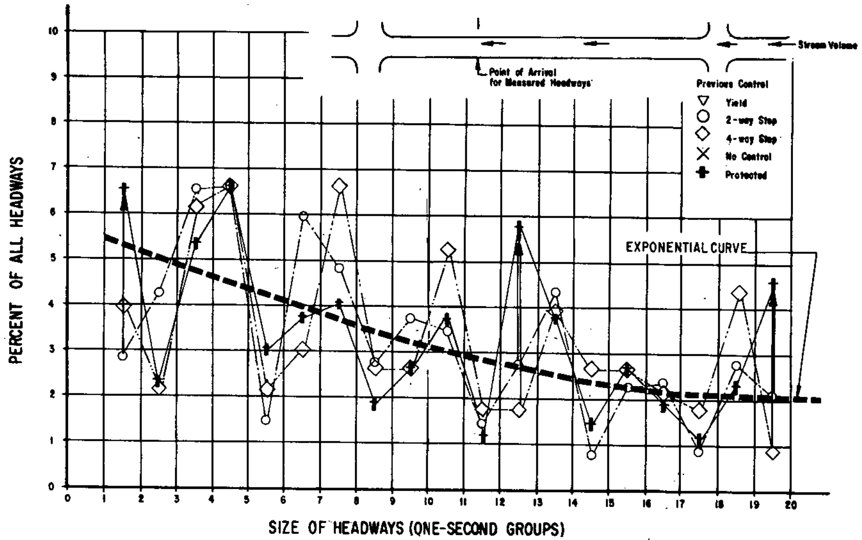


Figure 53. Distribution of headways of arrival, stream volumes of 150 to 200 vph.

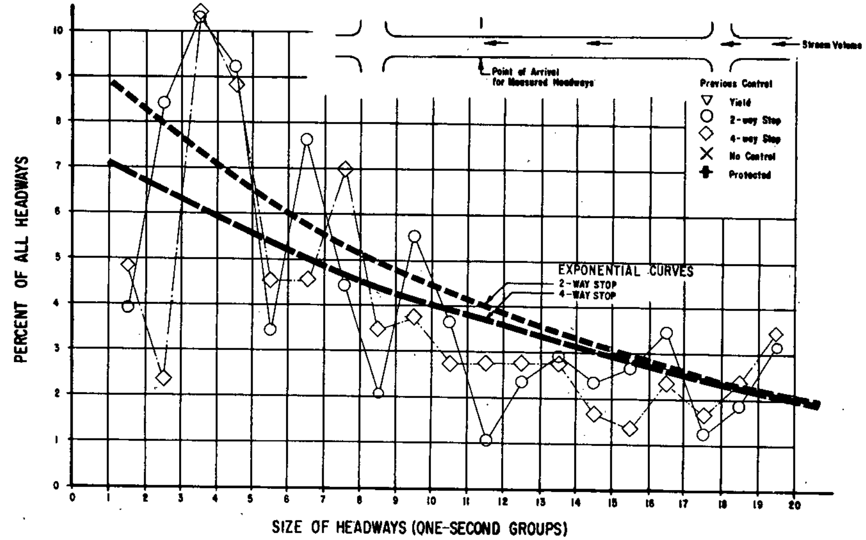


Figure 54. Distribution of headways of arrival, stream volumes of 200 to 300 vph.

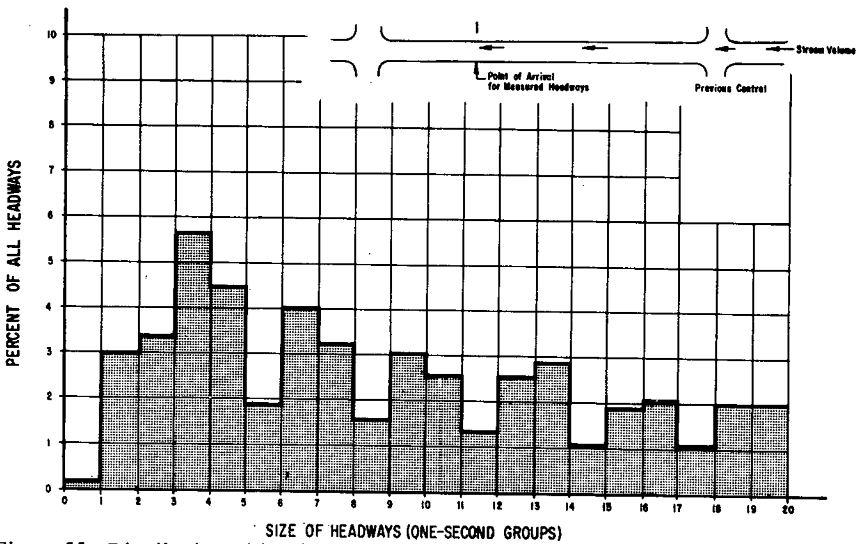


Figure 55. Distribution of headways of arrival, all volumes and all controls.

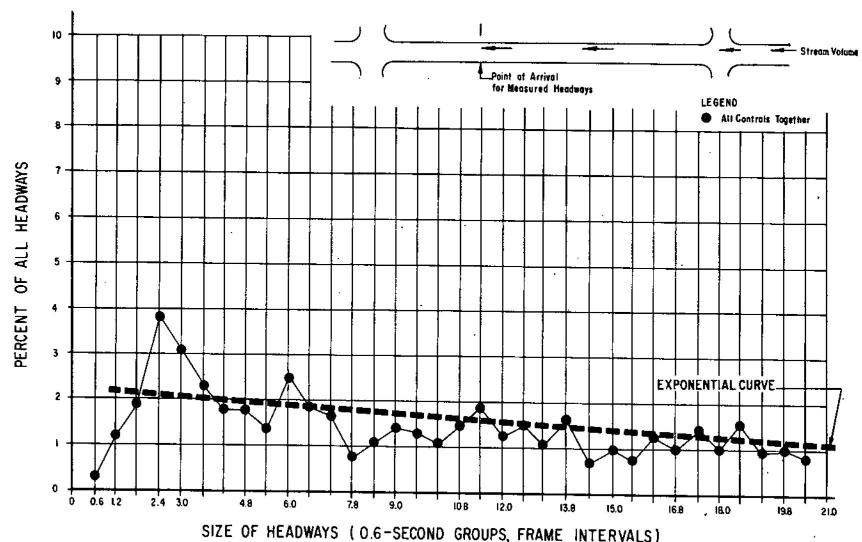


Figure 56. Distribution of headways of arrival, by frame, stream volumes of 100 to 150 vph.

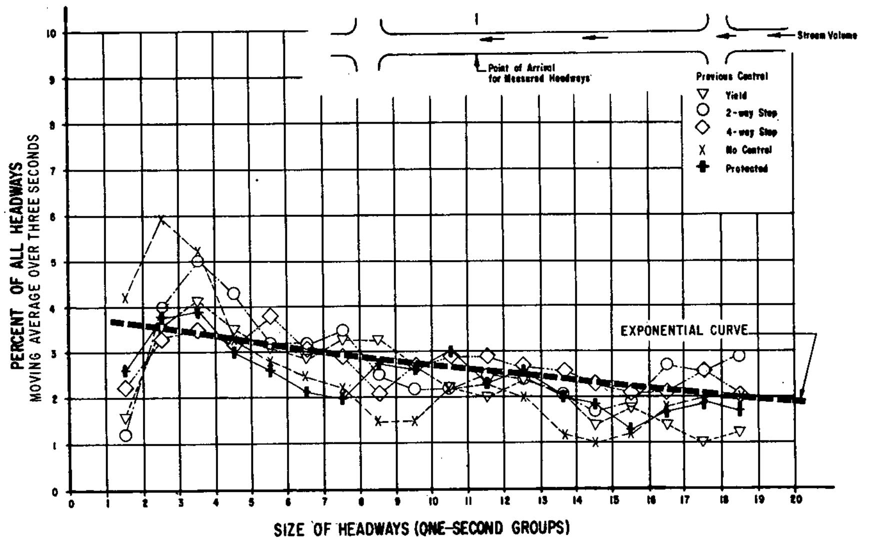


Figure 57. Distribution of headways of arrival, smoothed, stream volumes of 100 to 150 vph.

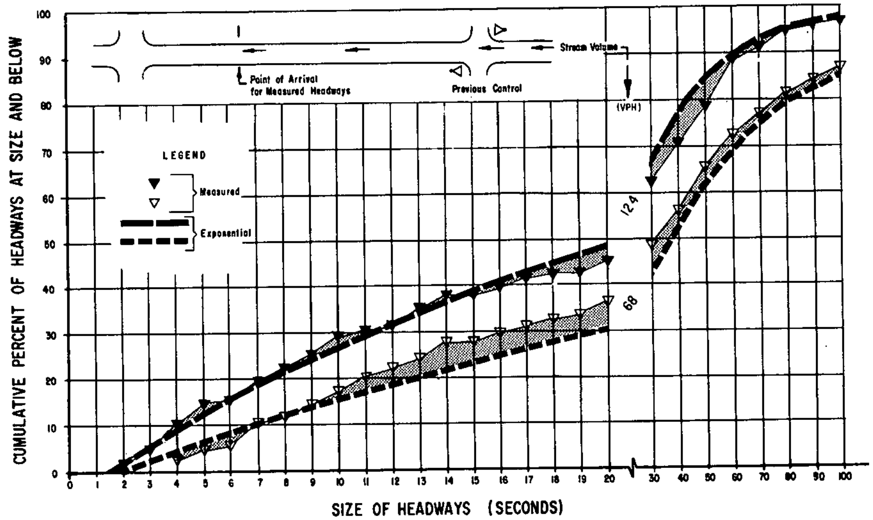


Figure 58. Cumulative distribution of headways of arrival; previous control—YIELD.

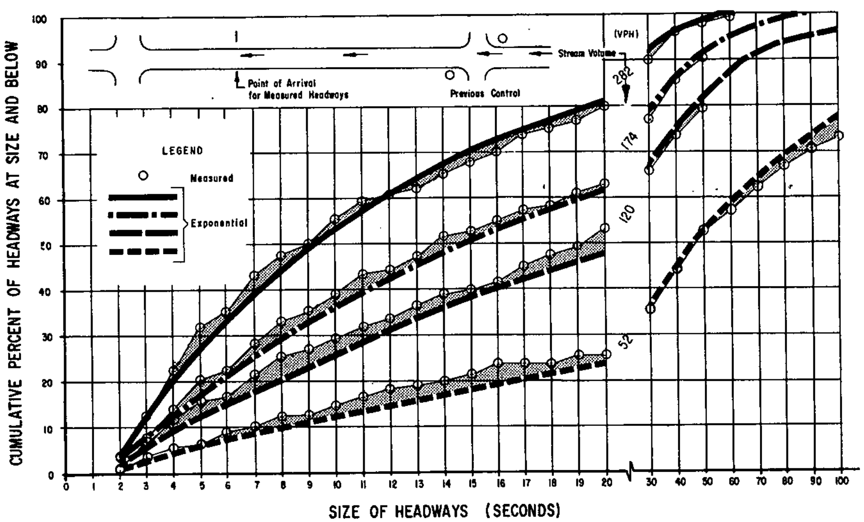


Figure 59. Cumulative distribution of headways of arrival; previous control—two-way STOP.

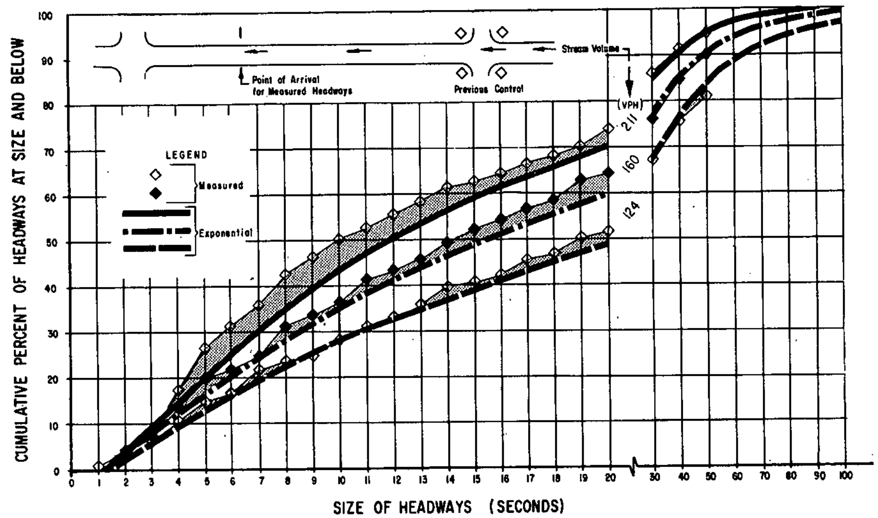


Figure 60. Cumulative distribution of headways of arrival; previous control—four-way STOP.

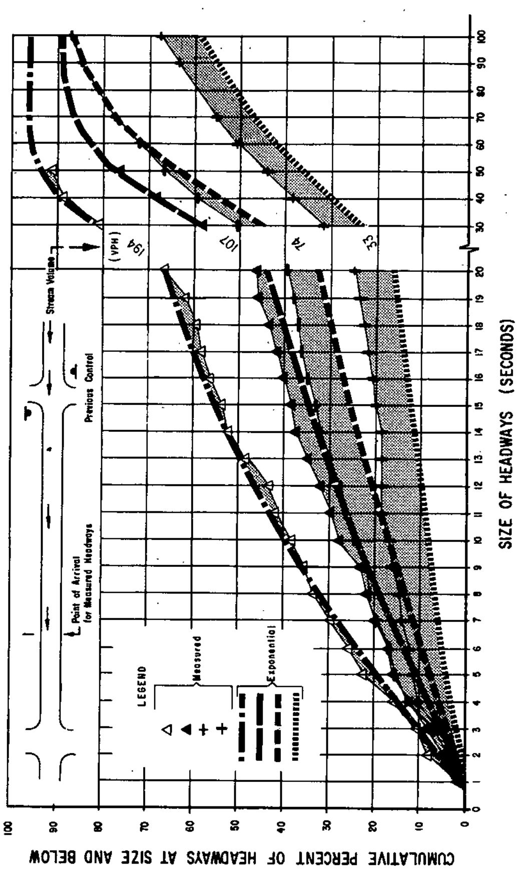


Figure 62. Cumulative distribution of headways of arrival; previous control—protected by YIELD *or* STOP.

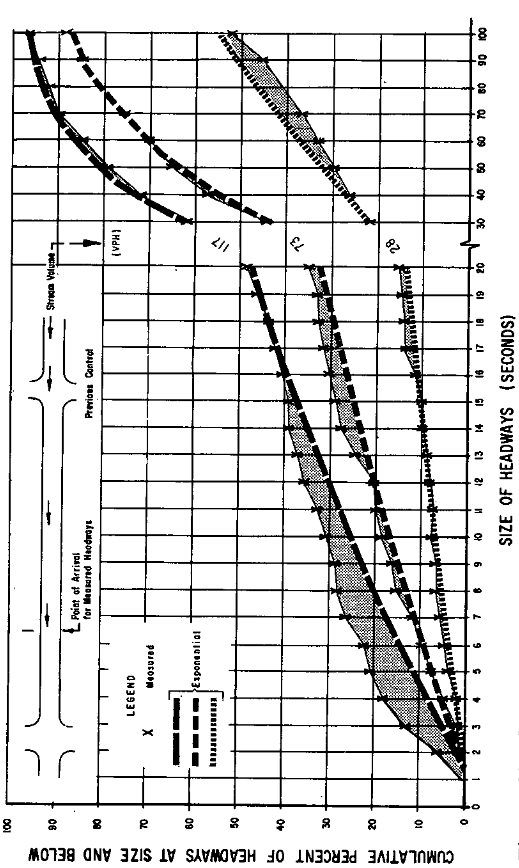


Figure 61. Cumulative distribution of headways of arrival; previous control—none.

results found in the analysis of arrival headways. The results seem to indicate that, in general, YIELD or STOP control does not rearrange the headway distribution on the minor street in any but a random manner at the major-street volumes and minor-street volumes between 0 and 400 vph.

Accidents

Accident records of the study intersection were gathered, tabulated and analyzed to determine if some preliminary relationships could be found between the accident experience and type of control. A study was also made of the obedience of the drivers, based on legal requirements, in using the controls at the study intersections. The results of these analyses are given in the following. In some cases, although the number of reported accidents was relatively small, the period of coverage was quite long. It is impossible from these data, therefore, to anticipate accurately the kinds of accidents that will occur or the conditions under which they are most likely to happen with each type of control, but they do provide useful information on overall rates.

Analyses of the intersection films were also made to obtain data on the obedience of drivers under each type of control.

All of the intersections studied were in residential areas with shopping districts nearby. The average daily traffic ranged from 2,350 to 5,500 vpd. Most drivers were familiar with the area, being shoppers, or commuters, or drivers of various service vehicles. During peak periods commuters comprised a large percentage of the total. In La Grange Park and Wilmette the major rush-hour flows were to and from the train stations, whereas in Skokie they were to and from the expressway. The off-peak and a portion of the evening peak periods were influenced by shopping habits and store hours. The high peak-hour volumes coincided on both major and minor streets during peak hours, with the exception of Kensington and Woodlawn where Woodlawn Avenue traffic had a late AM peak period caused by the opening of local businesses. The conditions at neighboring intersections, where supplemental data were obtained, were similar to those at the study intersections.

Accident records were obtained from the police departments of Wilmette, Skokie, and La Grange Park for the following intersections:

Site A—(i) Fifth Street and Linden Avenue—uncontrolled
(ii) Fifth Street and Greenleaf Avenue—YIELD
Site B—(i) Kirk Street and Kostner Avenue—uncontrolled and YIELD
Site C—(i) Kensington and Woodlawn Avenues—uncontrolled and YIELD
(ii) Kensington and Richmond Avenues—uncontrolled and YIELD

Kensington and Richmond has not been discussed previously. It is a YIELD-controlled intersection handling a total of 200 vehicles from all approaches in the peak hour

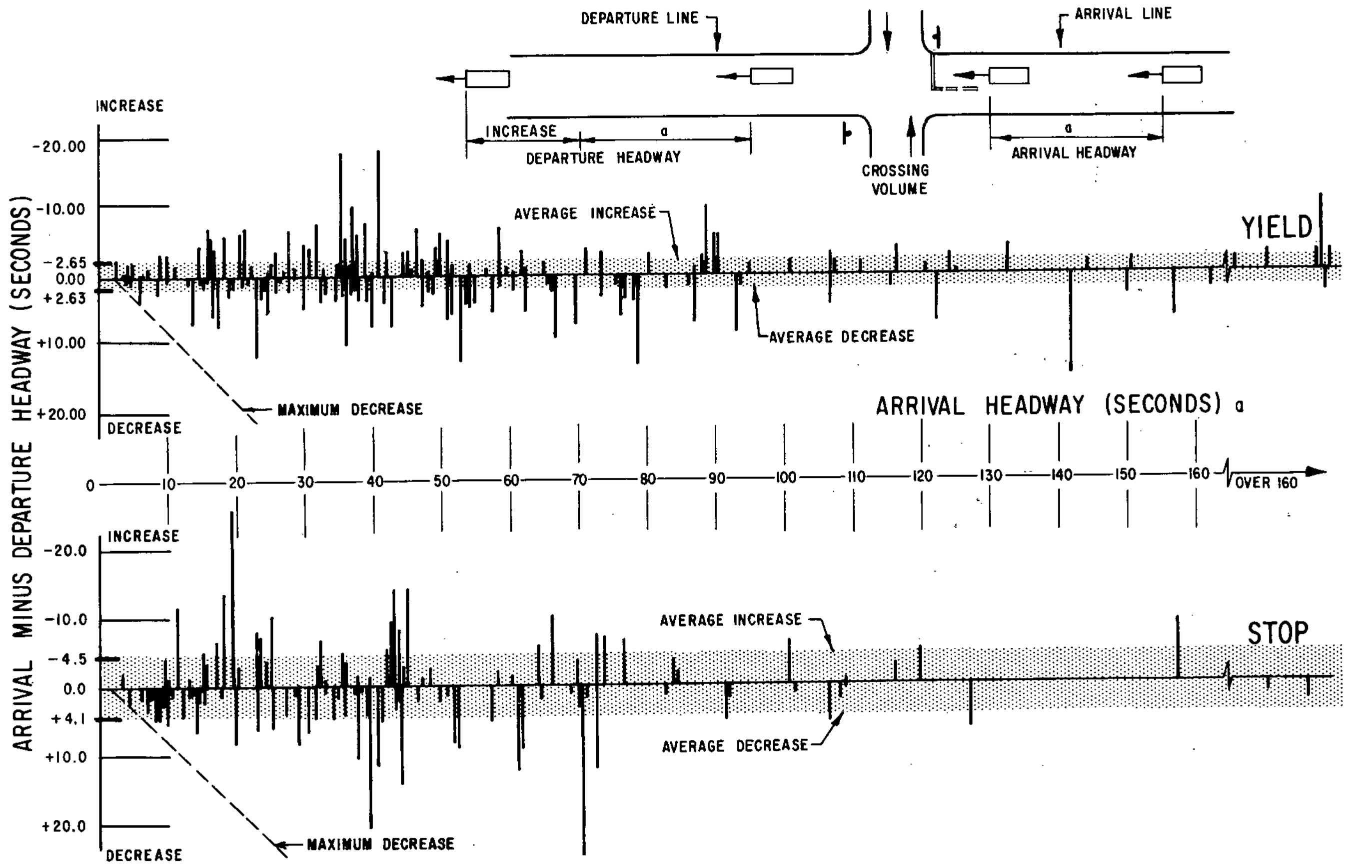


Figure 63. Change of arrival and departure headways with major-street volume of 0 to 100 vph.

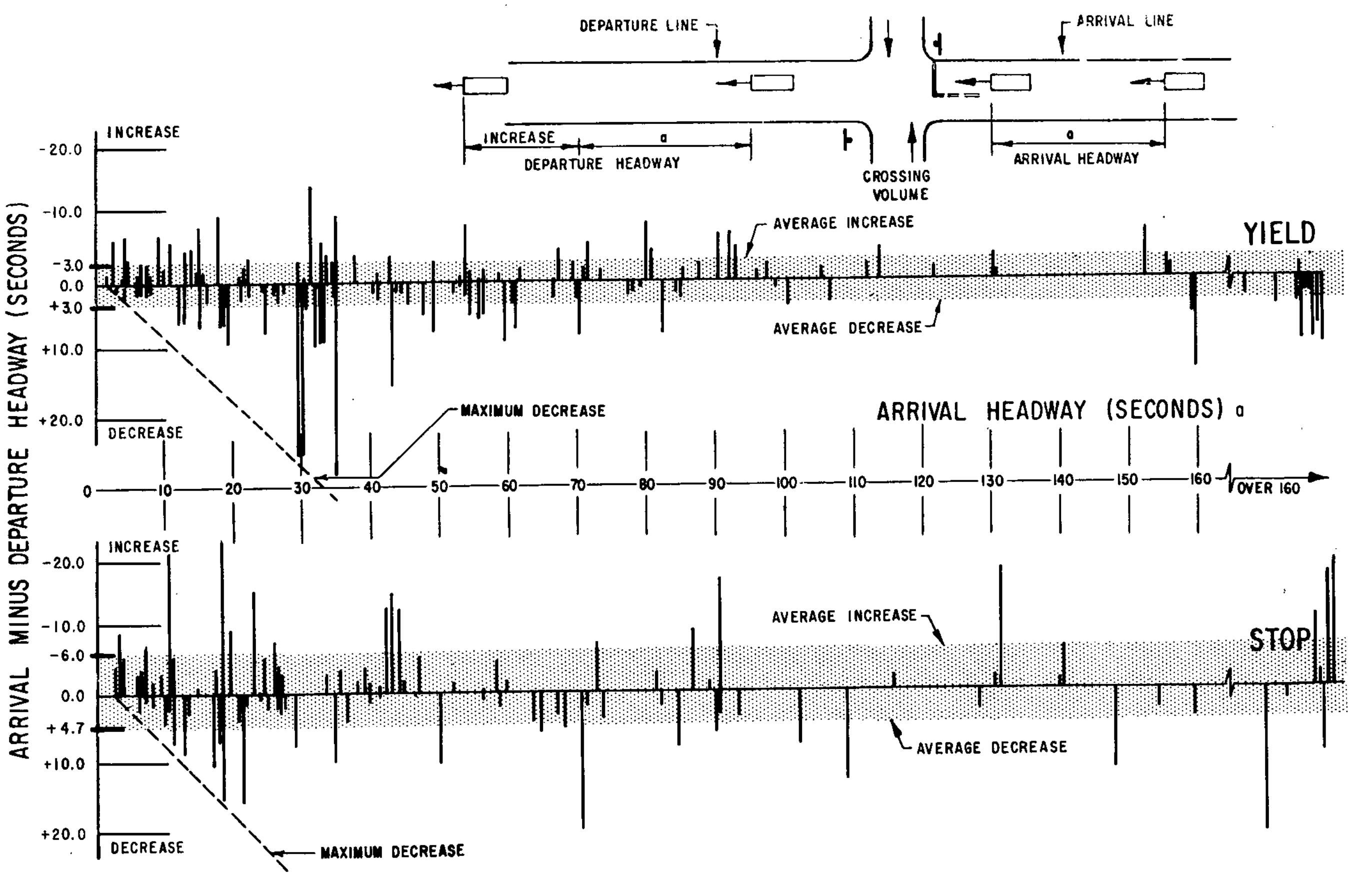


Figure 64. Change of arrival and departure headways with major-street volume of 100 to 400 vph.

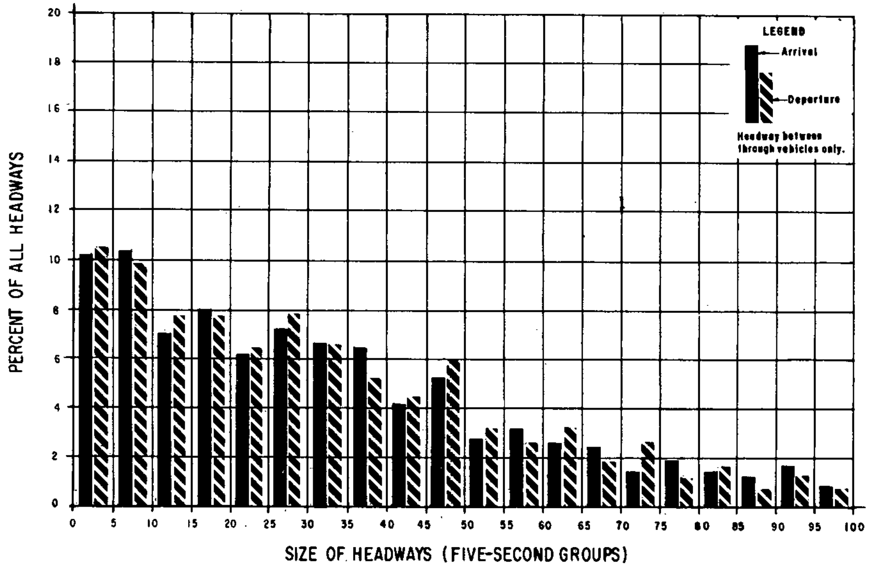


Figure 65. Distribution of headways of arrival and departure on minor streets under YIELD *control for major-street volume of 0 to 100 vph.*

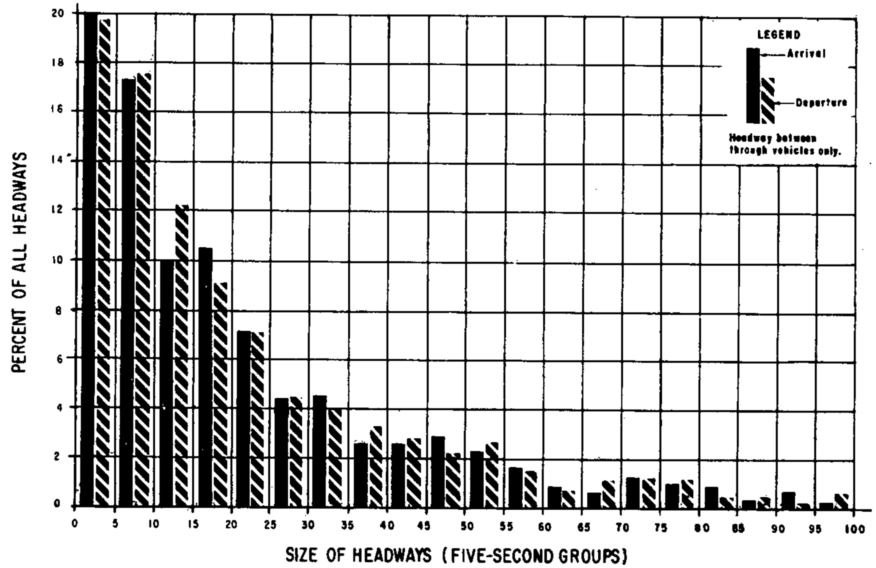


Figure 66. Distribution of headways of arrival and departure on minor streets under YIELD *control for major-street volume of 100 to 200 vph.*

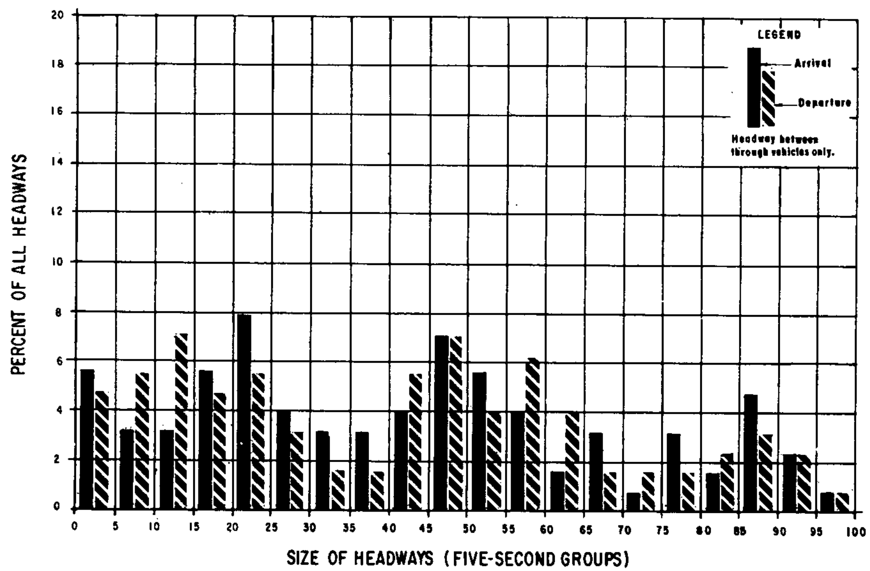


Figure 67. Distribution of headways of arrival and departure on minor streets under YIELD *control for major-street volume of 200 to 400 vph.*

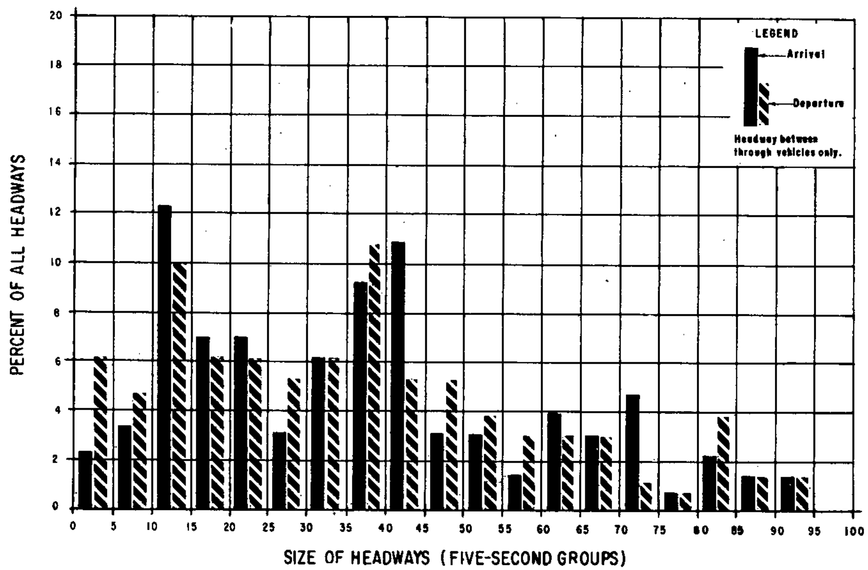


Figure 68. Distribution of headways of arrival and departure on minor streets under STOP *control for major-street volume of 0 to 100 vph.*

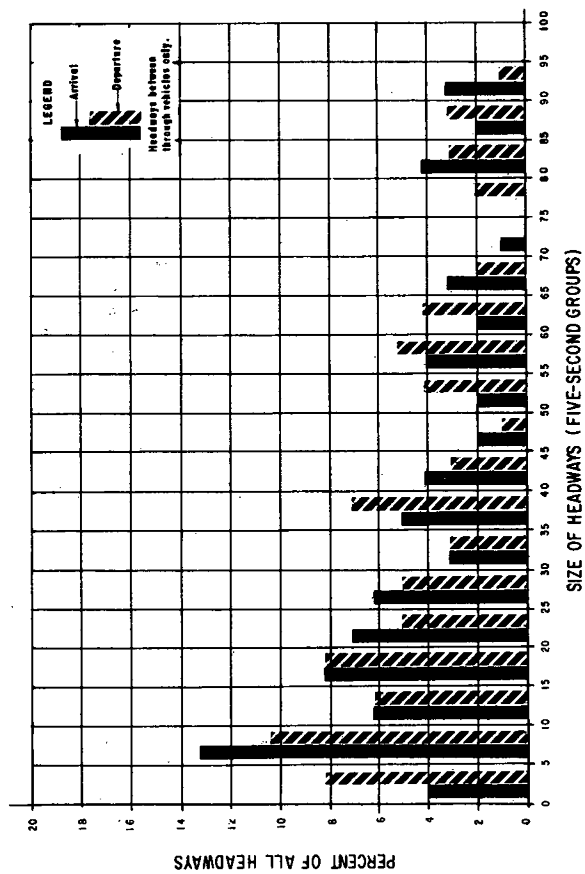


Figure 69. Distribution of headways of arrival and departure on minor streets under STOP *control for major-street volume of 200 to 400 vph.*

and is one block south of Kensington and Woodlawn (see Fig. 10). It was chosen so as to provide information on safety characteristics comparable with that gathered at Kensington and Woodlawn. This enabled an analysis of the effect on safety that occurred from controlling the major volume at Kensington and Woodlawn. Richmond yields to Kensington, therefore controlling the minor flow. The sight distance conditions here are similar to those at Kensington and Woodlawn.

For this analysis, only accidents which could be attributed to the intersection traffic and its control were studied. All accidents were right-angle collisions, including two with bicycles at Kensington Avenue, except one rear-end collision on Kirk Street. Several nonrelated one-car accidents in and near the intersections were disregarded.

Information was available during and after the study period for intersections where controls were changed, but it was not used because time between changes was too short to show significant results. As a matter of interest, there were no reported accidents at intersections when a change was made from uncontrolled to YIELD control. However, two accidents occurred within three months at intersections changed from YIELD to two-way STOP control. The first, involving a bicycle, was at Fifth Street and Linden Avenue. The other occurred at Kirk Street and Kostner Avenue.

The portion of the police records used related to (a) time of accident, (b) type (right angle, rear end, etc.),

TABLE 1

INTERSECTION ACCIDENT INDICES

INTERSECTION	AVERAGE NUMBER OF ACCIDENTS ON EACH APPROACH PER YEAR				AVERAGE NUMBER OF ACCIDENTS AT INTERSECTION PER YEAR	PERCENT DECREASE YIELD VS UNCONTROLLED	PERCENT OF ACCIDENTS UNDER INDICATED CONDITIONS		ACCIDENTS INVOLVING VEHICLES ON INDICATED APPROACH [1]			
	N	S	E	W			DAYLIGHT	DRY PAVEMENT	N	S	E	W
Fifth Street (N-S) Linden Avenue (E-W) (uncontrolled)	3.27	0.73	2.91	1.09	4.00	—	82	27	2.00	0.44	1.78	0.67
Kirk Street (E-W) Kostner Avenue (N-S) (uncontrolled)	0.00	2.18	1.64	1.64	2.73	—	100	40	0.00	1.50	1.12	1.12
Kirk Street (E-W) Kostner Avenue (N-S) (YIELD control)	0.41	0.61	0.61	0.41	1.02	63	100	60	0.28	0.42	0.42	0.28
Kensington Avenue (N-S) Woodlawn Avenue (E-W) (uncontrolled)	0.00	1.85	0.00	1.85	1.85	—	50	50	0.00	2.16	0.00	2.16
Kensington Avenue (N-S) Woodlawn Avenue (E-W) (YIELD control)	0.43	1.00	0.57	0.86	1.43	23	90	70	0.50	1.17	0.67	1.00
Kensington Avenue (N-S) Richmond Avenue (E-W) (uncontrolled)	0.73	1.09	0.73	1.09	1.82	—	60	80	—	—	—	—
Kensington Avenue (N-S) Richmond Avenue (E-W) (YIELD control)	0.31	1.09	0.62	0.78	1.40	23	89	33	—	—	—	—

[1] Per million vehicles per year using intersection. [2] Per million vehicles per year.

(c) pavement conditions (dry, wet, icy, snowy), and (d) intersection control type. These data were analyzed to see if relationships were present which would indicate any change in the hourly or monthly pattern of accident frequency between uncontrolled and YIELD conditions. The percentage of accidents at various intersections was tabulated in relationship to frequency of occurrence during daylight hours and with dry pavement conditions.

The accident data were stratified according to monthly and hourly distribution, and by light conditions and pavement conditions.

An analysis was made of the annual accident rate as affected by change in control (Fig. 70). At three intersections in different communities where YIELD control was imposed at previously uncontrolled intersections, there was a period varying between 15 months and three years after the installation during which the accident rate was substantially lower. The former rates were between one and three accidents per year. This indicates a likelihood that there is an adjustment interval during which the driver is quite aware of the new control and is abnormally cautious.

Kirk and Kostner showed a rate of about 2.5 accidents per year under uncontrolled conditions. No accidents were reported for 15 months after change to YIELD control. Following this initial period, the rate became about two accidents per year. The overall annual decrease was 63 percent (Table 1).

INTERSECTION ACCIDENTS PER MILLION VEHICLES	VOLUME ON INDICATED APPROACH (MILLION VEHICLES PER YEAR)				ACCIDENTS INVOLVING VEHICLES ON INDICATED APPROACH [2]			
	N	S	E	W	N	S	E	W
2.44	0.297	0.297	0.629	0.415	11.02	2.44	4.62	2.63
1.87	0.619	0.608	0.135	0.095	0.00	3.59	12.11	17.21
0.70	0.619	0.608	0.135	0.095	0.66	1.00	4.52	4.27
2.16	0.237	0.319	0.142	0.158	0.00	5.79	0.00	11.69
1.67	0.237	0.319	0.142	0.158	1.71	3.14	4.03	4.63
—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—

Kensington and Woodlawn averaged about two reported accidents per year under uncontrolled conditions (Fig. 70). There was one accident almost immediately after change to YIELD control, followed by a three-year period without any accidents being reported, after which the accident rate rose to a level higher than for the previous, uncontrolled condition. It should be noted that it is the heavier flow which is controlled at this intersection. Data were also obtained for the adjacent intersection of Kensington and Richmond. Here, the initial uncontrolled condition produced two to three accidents per year and the number of accidents became nil for about two years after the change to YIELD control, but then returned to approximately the original level. Here again the heavier flow is protected by the YIELD control. The overall change for each of these intersections was about a 23 percent decrease on an annual basis.

There was a fairly high annual accident incidence for Fifth and Linden while operated as an uncontrolled intersection over a 2½-year period. Fifth and Greenleaf, one block north of Fifth and Linden, showed no accidents over a slightly longer period with YIELD control, even though cars parked on the major street resulted in pronounced sight obstruction.

The accidents plotted by month for the intersections of Kensington and Woodlawn, Kensington and Richmond, and Kirk and Kostner (Fig. 70) indicate a rise in the number of accidents during the spring and summer months (April to September) after the uncontrolled intersection was changed to YIELD control. The most noticeable change in monthly distribution was at Kensington and Woodlawn where 89 percent, compared to 25 percent before, of the accidents occurred between September and December.

When the accidents were plotted by hour of the day and compared between uncontrolled and YIELD situations (Fig. 71), Kensington and Woodlawn again exhibited a changed pattern. With YIELD control, the intersection had more accidents during the evening peak period than when uncontrolled. The changes in distribution on Kensington may have been largely a result of the major flow being controlled at Woodlawn, inasmuch as at the neighboring intersection at Richmond, which yields to Kensington, there was no radical redistribution. At Kirk and Kostner there was a similar distribution with two control conditions, but all of the accidents occurred during off-peak periods. This can be explained by the large ratio of major-street vehicles present during peak periods, which inhibited the smaller volume of minor-street drivers from accepting potentially dangerous situations. When approaching the intersection during off-peak periods, drivers observed less major-street cross traffic and tended to go through the intersection with less reduction in speed.

Even though few accidents occurred, a fairly long period of exposure was studied. The trends indicate that when a control is changed there may be a predictable redistribution of the hourly and monthly accident patterns. Being able to anticipate changes in accident characteristics would be helpful in developing warrants for placement of these controls and signs.

TABLE 2

HAZARDOUS SPEED INDEX

INTERSECTION	SAFE APPROACH SPEED (MPH) N	S	E	W	INDEX = APPROACH SPEED / SAFE APPROACH SPEED N	S	E	W
Fifth Street (N-S) Linden Avenue (E-W) (uncontrolled)	16	17	16	34	1.24	1.07	1.49	0.68
Fifth Street (N-S) Linden Avenue (E-W) (YIELD control)	16	17	16	34	1.16	1.06	1.41	0.50
Fifth Street (N-S) Linden Avenue (E-W) (STOP control)	16	17	16	34	1.10	1.09	1.41	0.70
Kirk Street (E-W) Kostner Avenue (N-S) (YIELD control)	28	28	24	24	0.87	0.99	0.78	—
Kirk Street (E-W) Kostner Avenue (N-S) (STOP control)	28	28	24	24	0.85	0.90	0.75	0.70
Kensington Avenue (N-S) Woodlawn Avenue (E-W) (YIELD control)	30	21	24	26	0.62	1.18	0.90	0.84

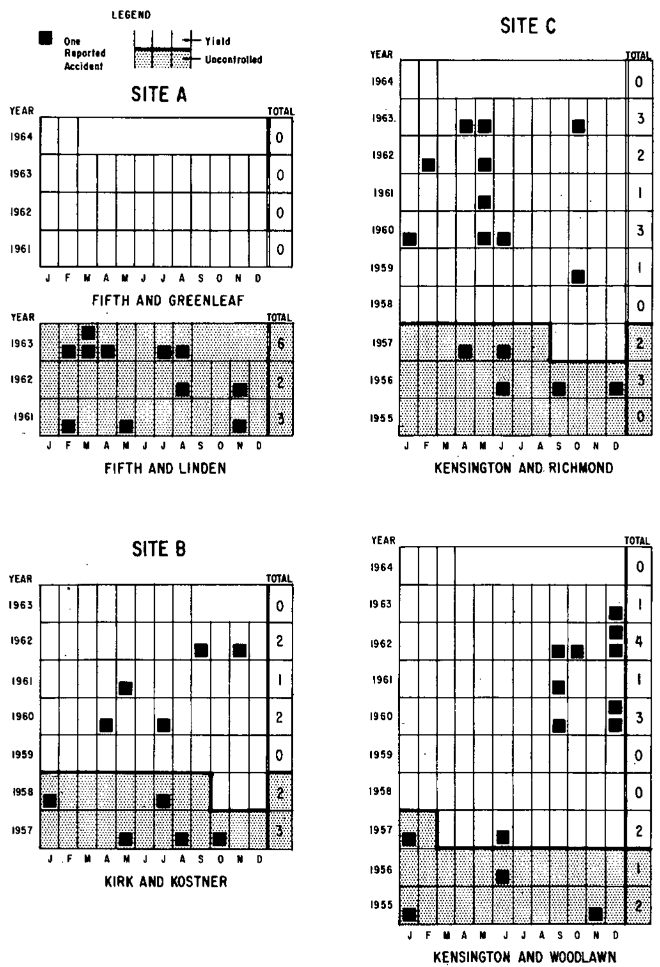


Figure 70. Yearly and monthly accident history of study site intersections.

The situation having the highest accident frequency at uncontrolled and YIELD intersections was under the following conditions: (a) daylight hours; (b) wet, snowy, or icy pavements; and (c) poor sight distance combined with high approach speeds (Tables 1 and 2). This does not apply, however, at Kensington and Woodlawn, where YIELD signs control the major flow of traffic. The intersection becomes increasingly accident prone during good driving conditions. This is probably a result of the over-restricted driver who becomes disobedient and disrespectful of a control that he believes should be on the other street.

An index was compiled to show the number of accidents on each leg on an annual basis. When these were totaled and divided by two, the average number of accidents per year for the entire intersection was obtained. The high-accident approaches to each intersection can be detected from Table 1.

When the indices for each leg are analyzed, it becomes apparent that certain approaches are more critical than others. At the intersections studied, it was found that one of the legs of the major traffic flow was involved in more accidents than the other. This is likely to occur at many intersections. Therefore, it was concluded that the hazard on each leg should be analyzed separately.

A volume study showed the relationship of major- to minor-street traffic and revealed those cases where the major flow was controlled. The hourly volume variations for each intersection were used to arrive at average daily traffic (see Figure A-1). From these values, the annual volume (in millions of vehicles) passing through each intersection was estimated and an index of accidents per million vehicles was calculated. Again, the individual

intersection approaches were separated in hopes of finding accident patterns. These separate indices were computed by dividing the average number of accidents per year on a leg by the total number of vehicles passing through the entire intersection. When added together and divided by two, the resulting index is an average number of accidents per year for the intersection. Carrying this principle one step further, the total average number of accidents per year on a leg was divided by the number of vehicles per year in millions, on that approach, to arrive at still another index. The objective of developing this variety of indices was to compare one with another to determine the value of each in describing the accident history and quality of the intersection.

The intersections of Kirk and Kostner and Kensington and Woodlawn showed a definite decrease in accident rate based on intersection volume after a change from uncontrolled to YIELD-control conditions. Based on intersection volume, the accident rate on the north leg of Kirk and Kostner increased slightly, whereas the other legs showed decreases. Based on intersection volume, the accident rate on the north and east legs of Kensington and Woodlawn rose with the change in control. The investigation of the accident rate on each leg, based on the volume on that leg, leads to the same general results. However, the low volumes resulted in much higher rates.

Where speed data were available, a small preliminary study was made of a hazardous-speed index developed as a tool to investigate to what extent the intersection was accident prone because of the unsafe approach speeds used by drivers. The index was the ratio of the measured average approach speed to the safe approach speed (Table 2). When compared with accident records for each leg of each intersection, a high hazardous-speed index was found to correlate with a high accident rate for that leg in every instance. This was especially true concerning accidents between vehicles on the north and east legs of Fifth and Linden while that intersection was uncontrolled. The normal right-of-way rule gave the north leg preference. However, the average east-leg vehicle approached at a speed 8.0 mph greater than the typical north-leg vehicle. About 70 percent of the east-leg-north-leg accidents consisted of a vehicle on the east leg colliding with a vehicle on the north leg.

The speed index may not be meaningful in comparing safety features of YIELD control with STOP control; the correlation of the speed index and accident rates previously seems to hold for each of the control conditions. It may be that this index in some way reflects the aggressiveness of drivers, and with it the accident-prone condition.

Driver Obedience

Obedience data of minor-street vehicles were obtained visually by interpretation of the films taken at the following intersections:

Site A—(i) Fifth Street and Linden Avenue—uncontrolled, YIELD, and two-way STOP
(ii) Fifth Street and Greenleaf Avenue—YIELD
(iii) Fourth Street and Greenleaf Avenue—YIELD

Site B—(i) Kirk Street and Kostner Avenue—YIELD and two-way STOP

Site C—(i) Kensington Avenue and Woodlawn Avenue—YIELD

Several sections of the Illinois law (7.06) relating to driver responsibility at YIELD and STOP signs, which appeared in Chapter Two, bear repeating here with a few further provisions, as follows:

Uncontrolled Intersections.—Vehicles Approaching or Entering Intersection. "(a) The driver of a vehicle approaching an intersection shall yield the right-of-way to a vehicle which has entered the intersection from a different highway. (b) When two vehicles enter an intersection from different highways at approximately the same time, the driver of the vehicle on the left shall yield the right-of-way to the vehicle on the right."

Stop Intersections.—Vehicle Entering Through Highway, Stop Intersection, or Stop Crosswalk. "The driver of a vehicle shall likewise stop in obedience to a Stop sign as required herein at an intersection where a Stop sign is erected at one or more entrances thereto although not a part of a through highway and shall proceed cautiously, yielding to vehicles not so obliged to stop which are within

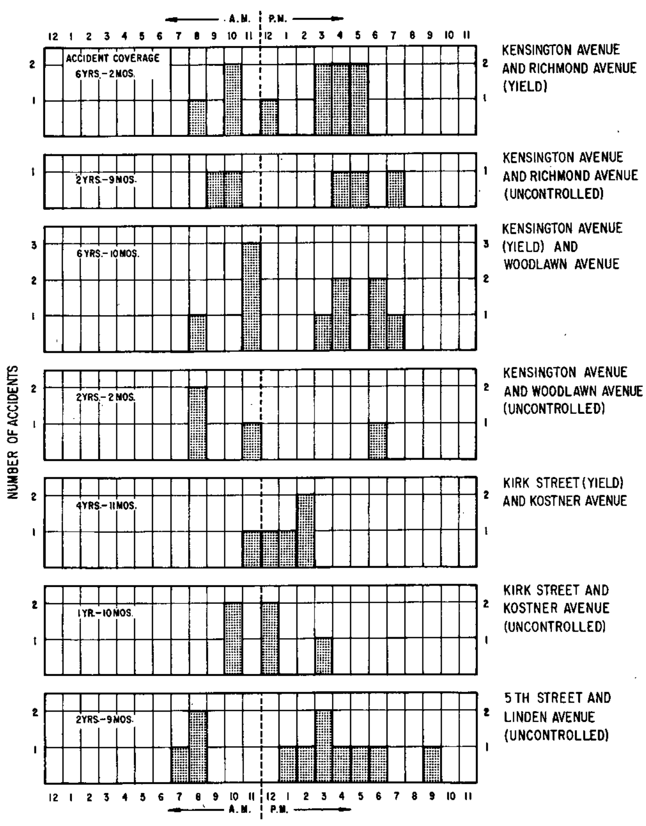


Figure 71. Hourly distribution of accidents at study site intersections.

TABLE 3
INTERSECTION OBEDIENCE DATA

INTERSECTION	PERCENT MAKING VOLUNTARY FULL STOP		PERCENT STOPPED BY TRAFFIC		PERCENT ENTERING: SLOW (< 5 mph)		PERCENT ENTERING: FAST (> 5 mph)		PERCENT ENTERING: 20 MPH OR GREATER	
	PEAK	OFF-PEAK	PEAK	OFF-PEAK	PEAK	OFF-PEAK	PEAK	OFF-PEAK	PEAK	OFF-PEAK
Fifth Street and Linden Avenue (uncontrolled)	1.0	0.0	20.0	14.0	20.0	35.0	59.0	51.0	1.0	1.0
Fifth Street and Linden Avenue (YIELD control)	0.5	1.0	28.5	13.5	30.5	25.5	40.5	60.0	2.0	1.0
Fifth Street and Linden Avenue (STOP control)	1.0	3.5	36.0	20.5	57.0	73.5	6.0	2.5	0.0	0.0
Kirk Street and Kostner Avenue (YIELD control)	0.0	2.0	26.0	24.0	33.5	30.5	40.5	43.5	1.0	1.0
Kirk Street and Kostner Avenue (STOP control)	8.5	11.5	39.0	30.0	47.5	48.5	5.0	10.0	0.0	0.0
Fifth Street and Greenleaf Avenue (YIELD control)	6.0	2.5	22.5	16.0	39.0	44.5	32.5	37.0	2.0	2.0
Kensington Avenue and Woodlawn Avenue (YIELD control)	0.0	1.5	7.0	17.0	30.5	27.5	62.5	54.0	13.0	13.0
Fourth Street and Greenleaf Avenue (YIELD control)	2.0	...	16.0	...	15.5	...	66.5	...	31.0	...

the intersection or approaching so closely as to constitute an immediate hazard, but then may proceed."

Yield Intersections.—Vehicles Entering Yield Right-of-Way Intersection. "(a) The driver of a vehicle in obedience to a Yield Right-of-Way sign shall reduce the speed of his vehicle to not more than 20 miles per hour and shall yield the right-of-way to other vehicles which have entered the intersecting highway either from the right or left or which are approaching so closely on said intersecting highway as to constitute an immediate hazard; but said driver having so yielded may proceed at such time as a safe interval occurs. (b) If a driver is involved in a collision at an intersection or interferes with the movement of other vehicles after driving past a Yield Right-of-Way sign, such collision or interference shall be deemed prima facie evidence of the driver's failure to yield right-of-way."

Vehicles were placed in various categories depending on their behavior at the intersection. In a voluntary full stop, a vehicle comes to a complete stop in the vicinity of the control sign, or before the curb line, without having been forced to do so by cross traffic. A vehicle which voluntarily slows to a near stop but maintains motion, at this point, at a speed below 5 mph, is referred to as having come to a "rolling stop." A "stopped by traffic" vehicle is one which had its progress impeded by the presence of cross traffic and was forced to reduce speed or make a full stop. The performance of all other vehicles was classified according to the speed at which they entered the intersection. A total of 4,408 vehicles was analyzed during peak and off-peak periods. The results of the study are given in Table 3.

The estimates of speed from the films were rather rough, and conclusions drawn should be regarded as preliminary. Furthermore, the decision as to what constituted a complete stop varied with each observer. Nevertheless, the results furnish interesting comparisons of YIELD and STOP controls.

Under uncontrolled conditions at Fifth and Linden, drivers apparently felt relatively unrestricted. They were not required to stop and consequently did so only rarely (about 1 percent of the time). The majority of the drivers not stopped by traffic entered the intersection at speeds greater than 5 mph but less than 20 mph. A large portion were in the 10- to 15-mph range. Of those vehicles entering faster than 5 mph, 8 percent more did so during the peak periods than during the off-peak periods. This indicates that the peak-period driver is more aggressive than the off-peak driver, even though more cross-street traffic is present.

The pattern was different under YIELD conditions, especially when the major-street volume was equal to or greater than the minor-street volume. The ratio of voluntary stops remained at about 1 percent at Fifth and Linden.

NUMBER OF VEHICLES SAMPLED			ESTIMATED DAILY VOLUME		
PEAK	OFF-PEAK	TOTAL	MAJOR STREET	MINOR STREET	A.D.T.
148	125	273	2,880	1,620	4,500
187	220	407	2,880	1,620	4,500
212	200	412	2,880	1,620	4,500
57	252	309	3,345	655	4,000
83	156	239	3,345	655	4,000
565	685	1,250	1,640	1,660	3,300
155	178	333	820	1,530	2,350
1,185	. . .	1,185	1,500	4,000	5,500

The percentage was also low at Kirk and Kostner. However, there was a slightly greater tendency to stop at Fifth and Greenleaf. A larger percentage of vehicles entered the intersections faster than 5 mph under YIELD control during off-peak than during peak periods. This was primarily the result of greater cross-traffic interference during peak periods. Thus, the driver on the minor street, realizing that he might have to yield, was more cautious.

At Kensington and Woodlawn and at Fourth and Greenleaf, the YIELD signs apply to the major flow of traffic. The peak-period driver rarely stopped unless forced to by cross traffic. There was a consistent tendency to travel faster than at intersections where the heavier volume was on the major street.

It is of interest to note the percentage of drivers at the various intersections passing YIELD signs faster than the legal speed of 20 mph. Where the intersection was either uncontrolled or YIELD controlled, 1 to 2 percent of the vehicles traveled faster than 20 mph. There was no significant difference in behavior under uncontrolled and under YIELD conditions. This small percentage appears to be uniform when the volume on the controlled street is greater than or equal to the uncontrolled street volume. However, when the volume of the controlled street surpasses that of the protected street, the disobedience rate rises markedly as the controlled volume increases. Kensington Avenue (the controlled volume) was almost twice that of Woodlawn Avenue, and the disobedience rate was 13 percent. A dramatic increase occurred at Fourth and Greenleaf, where the disobedience rate on Fourth Street was 31 percent. The controlled volume on Fourth Street varied from three to five times the volume on Greenleaf Avenue during peak periods. At this intersection only a small number of vehicles entered from the east leg and most of the west-leg vehicles turned right. Consequently, drivers on Fourth Street tended to be aggressive, knowing that the chances were slight that they would have interference from Greenleaf Avenue traffic. The indications are that, when the volume of the traffic controlled exceeds that of the protected flow, the level of disobedience of YIELD-controlled traffic will be high.

Three types of YIELD sign were in use during the study. At site A the signs were triangular and bore the message: YIELD RIGHT-OF-WAY. Site B had the new standard sign recommended in the *Manual on Uniform Traffic Control Devices* (7.07), which is triangular and bears the simple message: YIELD. At site C the sign was of the older trapezoidal form, with the message: YIELD RIGHT-OF-WAY. Although not studied in detail, there appeared

TABLE 4
RETURN OF DRIVER QUESTIONNAIRES AT OAK PARK CORRIDOR SITE

QUESTIONNAIRE STATION	BEFORE			AFTER		
	HANDED OUT	RETURNED NUMBER	RETURNED PERCENT	HANDED OUT	RETURNED NUMBER	RETURNED PERCENT
(*a*) PEAK PERIOD						
Division St.	250	93	37	275	74	27
Augusta St.	392	177	45	425	172	40
Total	642	270	42	700	246	35
(*b*) OFF-PEAK PERIOD						
Division St.	149	54	36	150	46	31
Augusta St.	150	45	30	136	49	36
Total	299	99	33	286	95	33

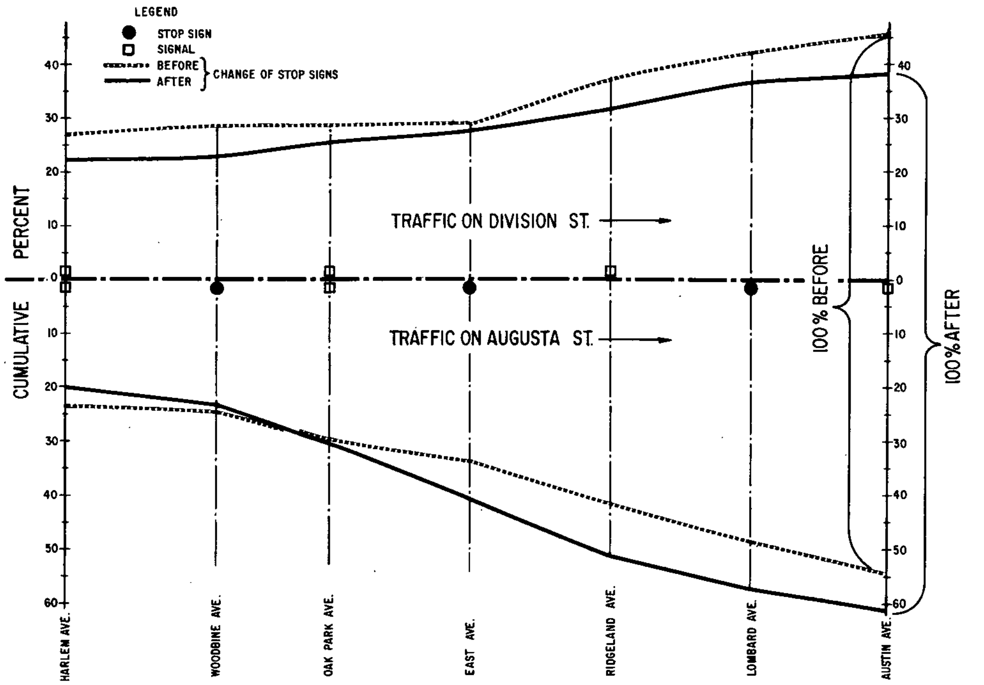


Figure 72. Traffic on Division and Augusta Streets approaching questionnaire stations.

TABLE 5

AVERAGE OF DRIVOMETER READINGS BEFORE AND AFTER CHANGE

ROUTES (ALL PEAK-PERIOD)	DISTANCE (MILES)	SAMPLE SIZE (RUNS)		DIRECTION CHANGE (5° VEHICLE TURN)		BRAKE APPLICATION (APPL. PLUS RELEASE)		SPEED CHANGE (4 MPH)	
		BEFORE	AFTER	BEFORE	AFTER	BEFORE	AFTER	BEFORE	AFTER
Division Street	1.64	16	7	54.6	67.0	9.4	10.0	103.4	103.8
Augusta Street	1.64	14	14	33.9	32.5	11.5	4.8[a]	114.6	66.2
S-route, Division to Augusta:									
via Oak Park Ave.	1.9	6	4	97.6	109.1	11.8	8.3	116.7	104.5
via East Ave.	1.9	6	4	103.9	110.0	9.4	8.8	114.4	103.3
via Elmwood Ave.	1.9	6	4	107.2	109.5	8.8	7.8	113.2	100.8
via Lombard Ave.	1.9	6	4	103.2	114.4	9.5	11.5	105.1	111.1
via Harlem Ave.	1.9	6	4	34.6	73.9	9.3	8.4	124.5	98.5

[a] Significant decrease. [b] Significant increase.

TABLE 6

QUALITY OF TRAFFIC FLOW INDEX [a]

ROUTE	AVERAGE SPEED, A (MPH)		AVERAGE SPEED CHANGES, B [b] (MPH)		AVERAGE DIRECTION CHANGES, C [b] (DEG)	
	BEFORE	AFTER	BEFORE	AFTER	BEFORE	AFTER
Division Street	17.2	17.3	88	90	58	73
Augusta Street	19.2	22.0	97	66	36	41
S-route, Division to Augusta:						
via Oak Park Ave.	20.5	19.2	90	83	94	108
via East Ave.	20.8	20.2	90	85	102	112
via Elmwood Ave.	21.6	20.4	90	82	107	112
via Lombard Ave.	19.8	17.8	85	89	104	114

[a] $Q = \frac{A \times 1{,}000}{(1+B)(1+C)}$ [b] Per running minute.

to be no difference in driver behavior attributable to the design of the sign. Drivers throughout the area have known YIELD signs for several years and apparently regard all types the same.

No vehicles were observed traveling 20 mph or faster on the minor street at the two-way STOP intersections. There are occasions when the driver will exceed this speed because he is not aware of the control. Table 3 shows that voluntary full stops are not common, regardless of whether intersections are uncontrolled or YIELD or two-way STOP controlled. The number of vehicles coming to a voluntary full stop under two-way STOP conditions was only slightly greater than at uncontrolled and YIELD intersections. The large percentage of rolling stops was attributed to (a) prevalence of local (familiar) drivers, (b) sight distance restrictions which encouraged drivers to creep up to obtain a suitable view of cross traffic (especially at Fifth and Linden), and (c) a lack of interest in the continued enforcement of the full stop in the Chicago metropolitan area. If the law is interpreted strictly, 53 to 76 percent of all drivers disobeyed the STOP signs. If only vehicles traveling faster than 5 mph are considered to be in violation, however, about 5 to 10 percent disobeyed.

TOTAL TIME (SEC)		RUNNING TIME (SEC)		STOP TIME (SEC)	
BEFORE	AFTER	BEFORE	AFTER	BEFORE	AFTER
342.6	340.5	281.7	275.1	60.9	65.4
307.3	268.9[a]	282.4	242.4[a]	24.9	26.5
342.6	355.0	310.2	305.8	32.4	51.2[b]
328.5	338.5	305.9	294.4	22.6	44.1[b]
317.3	334.9	297.0	294.4	20.3	40.5[b]
344.5	382.9	297.6	300.1	46.9	82.8[b]
340.0	342.5	303.5	294.9	36.5	47.6[b]

QUALITY OF TRAFFIC FLOW, Q		CHANGE, BEFORE TO AFTER (%)	
BEFORE	AFTER		RELATIVE TO DIVISION
3.3	2.6	−21	0
5.3	7.8	+47	+68
2.3	2.1	− 8	+13
2.2	2.1	− 4	+17
2.2	2.2	0	+21
2.2	1.7	−22	0

ROUTE OPERATION

The study of the effect of a set of STOP signs along a route on operation in a corridor in Oak Park (see Figs. 13 and 14) was studied with driver mail-in questionnaires and the Greenshields drivometer. Data were collected before the change in controls, and about one month after the change. The results of this study are discussed in the following.

Questionnaire Study

Before and after the STOP-control changes were made, questionnaires were handed out to eastbound drivers at two points at the exit from the corridor during a morning peak and an off-peak period. The two points (or stations) were located at the east end of the corridor at the Austin Avenue intersections with Division and Augusta Streets. Table 4 gives the number of questionnaires handed out at the two stations, and the number and percentage returned.

The questionnaire returns were first analyzed by combining them to obtain a general idea of the flow characteristics of eastbound peak-hour traffic through the corridor during the two study periods. Returned questionnaires were sorted by station, by peak or off-peak hour, and by before or after period. The data were then expanded proportionately to comparable levels of return. Finally, they were coded and tallied by the route taken through the corridor.

Assuming that the eastbound motorists passing the two stations were randomly sampled and that they returned the questionnaires in a random manner, results of the questionnaire returns were representative of all eastbound drivers passing the two stations.

The adjusted questionnaire returns were statistically tested to determine whether the proportions of drivers taking the various routes during the before period differed significantly from the proportion taking the same routes after the control changes on Augusta.

Several methods of grouping the results of the questionnaire study were tried in order to increase sample sizes for analysis. These are described in Appendix B. The method deemed most representative of the real situation is discussed here. The internal traffic was divided into several zones and combined with through traffic to investigate the cumulative change in volumes from the west end to the east end of the corridor.

The results for both Division Street and Augusta Street are plotted in Figure 72. The Austin Avenue percentages represent the proportional distribution of motorists moving easterly past the Division and Augusta Street questionnaire stations during a morning peak period.

Some of the north-south streets which intersect both Division and Augusta Streets (Harlem, Woodbine, Oak Park, East, Ridgeland, Lombard, and Austin Avenues) appear as ordinates on the graph. The percentage appearing at each of these streets is representative of that part of the total peak-period traffic on the two streets which moved easterly past the Austin Avenue stations.

It can be seen that the percentage of traffic moving along Division Street decreased with the control change

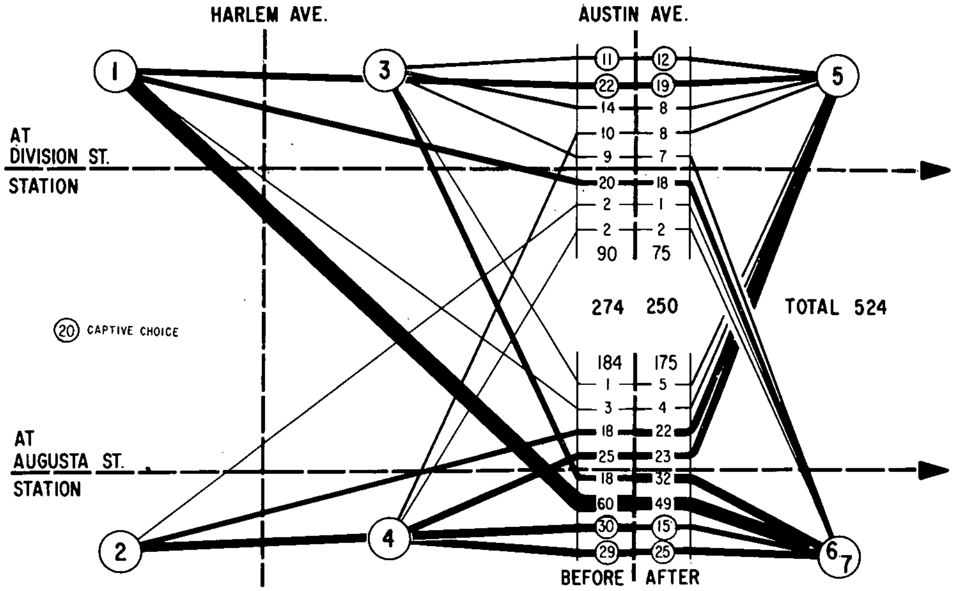


Figure 73. Origins and destinations of peak-period drivers before and after removal of STOP *signs on Augusta (based on questionnaire returns).*

on Augusta. Also, the traffic on Augusta Street increased for the most part after the change. The total shift is approximately 8 percent toward Augusta. It should be kept in mind that the nearby Eisenhower (Congress Street) Expressway (see Fig. 3) could have an influence on through traffic in this corridor.

Further studies were made to explain these findings. They included a small-scale origin-and-destination study, using the questionnaire returns, because origins and destinations obviously would influence the choice of Division or Augusta Streets as routes of travel.

All trip ends were summarized in seven large sectors (Figure 73), with sectors 1 and 2 west of Harlem Avenue, sectors 3 and 4 within Oak Park, and sectors 5, 6 and 7 east of Austin Avenue; Thomas Street (see Fig. 13) separated the odd-numbered sectors on the north from the even-numbered sectors on the south, except for sector 7 which designated downtown Chicago.

Figure 73 shows the number of drivers traveling between the different sectors who were questioned either on Division or Augusta during peak periods only, and compares the situation before and after the change of controls on Augusta. The values shown are unadjusted for relative sample sizes and, therefore, represent the "raw" data. It should be noted that very few trips were destined to downtown Chicago. This can be explained by the prox-

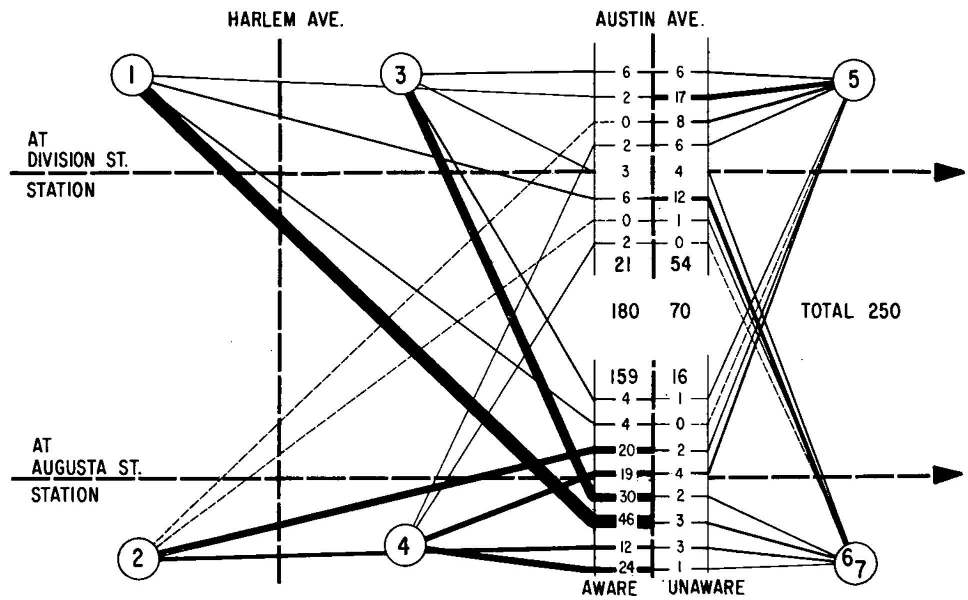


Figure 74. Origins and destinations of peak-period drivers by awareness of control change (based on "after" questionnaire returns).

imity of the Eisenhower (Congress Street) Expressway, which attracts most of the long trips. The trips using Augusta and Division in Oak Park were generally shorter. Sector 7, therefore, was included in sector 6.

Because the number of questionnaires returned in the before and after studies was not the same, the absolute values of the number of trips cannot be compared directly. The 274 answers to the before questionnaire represent about a 10 percent larger sample than the 250 answers to the after questionnaire.

In Figure 73, some of the trip numbers are circled to indicate "captive choice." This means that a driver with both origin and destination north of Thomas Street probably used only Division Street, and a driver with both origin and destination south of Thomas Street probably used only Augusta Street. The figure shows, however, that a few drivers detoured and used the more distant of the two streets.

Drivers going diagonally between sectors 1 and 3 and 6 and 7, or between sectors 2 or 4 and 5, had relatively free choice between Division and Augusta Streets. The tabulation shows a driver preference for Augusta Street before as well as after the STOP-sign change. For both the before and after conditions, the drivers traveling between zones diagonally opposite each other with respect to the corridor preferred to travel along Augusta. The preference for Augusta increased overall, however, after the change in control. Drivers traveling between sectors 1 and 6 or 7 showed negligible change in their preferences, as did those moving between sectors 4 and 5. It should be noted that in these two cases a large percentage was already using Augusta before the change in control was made. Trips between sectors 3 and 6 or 7 changed from 64 percent to 82 percent on Augusta, and trips between sectors 2 and 5 changed from 56 percent to 64 percent on Augusta. The overall shift to Augusta for those routes where a choice existed was on the order of 25 percent. This analysis indicates, therefore, that the pattern of traffic having a choice between the two streets shifted to Augusta as a result of the improved operation due to the removal of STOP signs. It should be recognized, however, that the results are based on a relatively small amount of traffic.

Another important consideration is presented in Figure 74. Each driver was asked if he had noticed the STOP-sign change on Augusta. Evidently, a large proportion of the drivers who regularly use Division Street had not realized that an improvement had been made on Augusta, even though the change was publicized in local papers. Those unaware of the change are shown on the right side of the figure. For example, none of the drivers between sectors 2 and 5 who still used Division Street knew of the change of signs. In contrast, almost all of those using Augusta (20 out of 22) had noticed the improvement.

It is evident from this discussion that, among all drivers returning questionnaires, many did not have a free choice between Augusta and Division because of their origins and destinations, and others did not use Augusta because they did not know of the improvement.

Driver comments on the returned questionnaires gave further evidence of the driver's reaction to the STOP-sign removal. These indicated that drivers were definitely in favor of the improved traffic conditions on Augusta Street. Among the drivers using Augusta during the peak period after the change of controls, 40 answered positively that they had rerouted their trips to Augusta. The number of drivers changing for each reason was: Removal of STOP sign, 23; Faster, smoother, 11; Other reasons, 6. The 11 drivers stating that traffic on Augusta was faster and smoother also probably meant that this was due to STOP-sign removal, although they did not explain. Other reasons were "better route," "better connection in Chicago," "better pavement," "change of scenery."

There were, however, two drivers who criticized the change of four-way STOP to two-way STOP because: "Turning into Augusta at four-way STOP was quicker and safer than at two-way STOP," and "Turning left from Augusta at four-way STOP was easier than at two-way STOP."

Although four-way STOP provided some advantages for minor-street traffic and for left turns from Augusta, it appears that most drivers preferred the improved through flow on Augusta provided by the two-way STOP control.

Volume Counts

During the before and after periods, peak and off-peak traffic counts were made at key intersections throughout the study area. The counts obtained at six of these intersections are shown in Figure 75.

It was intended that these before and after volume counts would provide further information on route choice. However, delays during the course of the study caused the after portion to extend to within one week of Christmas. This, plus extreme cold and bad weather during the period when volume counts were taken, eliminated any possibility of direct comparison of volumes. The questionnaire, however, had been handed out before the bad weather, thereby making it valid. As indicated in Figure 76, there was an overall decrease in traffic. The data were probably further disrupted by patterns of travel occasioned by the Christmas holidays.

Drivometer Data

The drivometer was used to collect data on stream operation, driver actions, and vehicle dynamics. Measurements were made on the anticipated major alternates through the corridor before and after the change in control along Augusta. The routes included the two major streets of Augusta and Division (see Figure 13) and several S-shaped routes which began at the intersection of Division and Harlem and finished at the intersection of Augusta and Austin. The north-south avenues (Harlem, Oak Park, East, Elmwood and Lombard) connect the west-to-east sections of Division and Augusta Streets for the major S-shaped routes.

The drivometer data were automatically processed and tabulated as discussed in Appendix B. The several runs

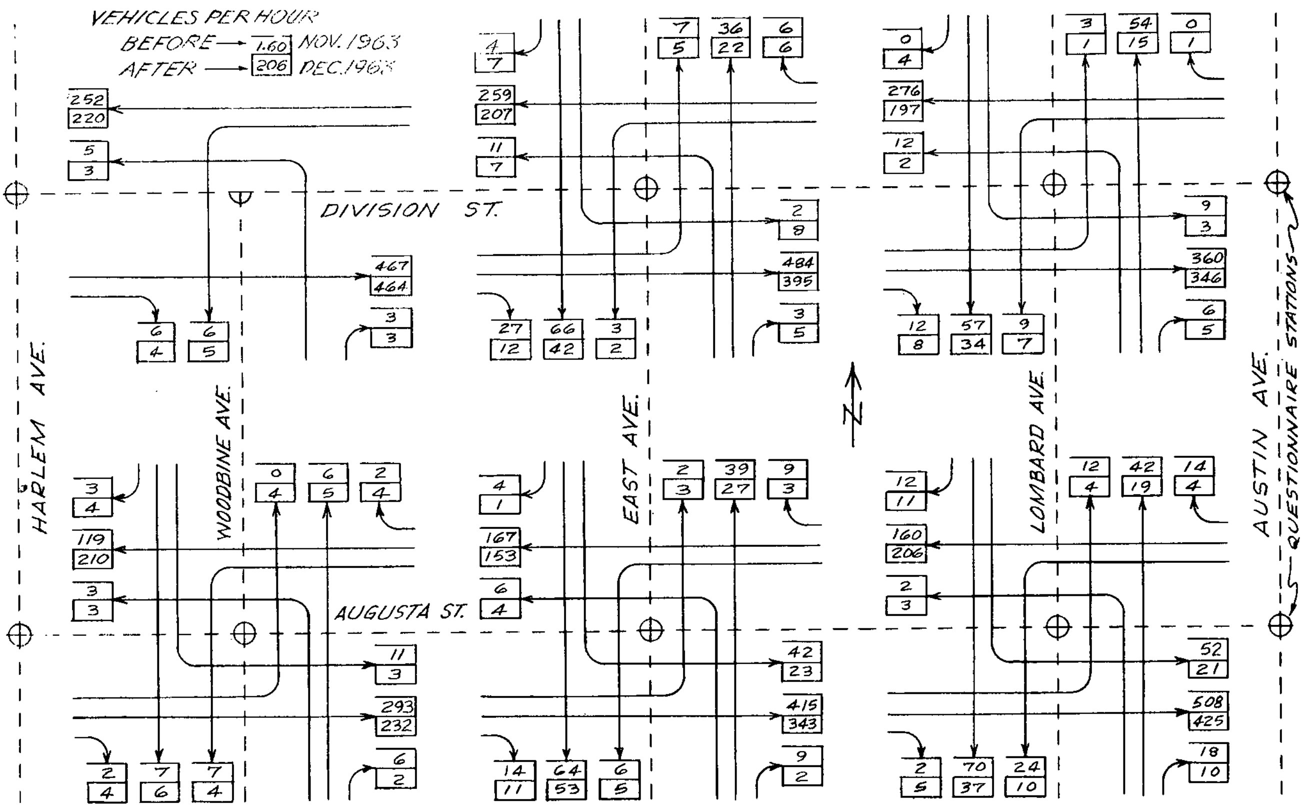


Figure 75. Average weekday morning peak-hour traffic along Division and Augusta Streets before and after removal of STOP *signs.*

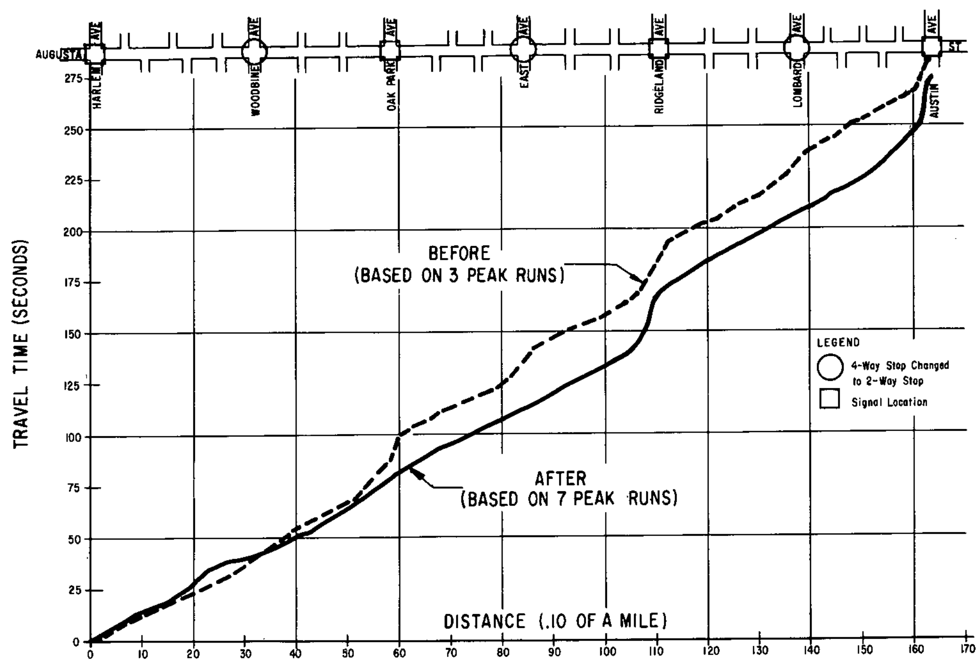


Figure 76. Travel time on Augusta Street before and after control change.

on the same route before or after the removal of the STOP signs were averaged. The resulting values for the important routes and measurements are given in Table 5.

Statistical tests were run on these data using the F-test and a variation of the t-test, and the statistical confidence intervals of before and after averages were analyzed.

Although many drivometer runs were made through the area, the sample sizes are still relatively small and somewhat affected by the habits of individual drivers. Small differences in the results of the average values are, therefore, not considered relevant to the influence of STOP-sign removal in the study of the corridor traffic, as shown in the before and after conditions.

Table 5 indicates the different units of direction change, brake application, and speed change. Running time was subtracted from total time to determine the stopped time. The values show that there was little change on Division Street between before and after conditions. The total time for the run on Division was about 5.7 min. On Augusta Street, however, a sample (which included some runs under wet pavement conditions) of 14 runs before and 14 runs after showed significant reductions in brake application (from 12 to 5), speed change (from 115 to 66 changes), total time (307.3 sec before to 268.9 sec after), and running time (282.4 sec before to 242.4 sec after).

It was surprising that the stopped-time delay on Augusta increased by 1.5 sec. The increase can be considered negligible, but it was expected that the removal of STOP signs would cause a significant decrease here. In order to investigate this a bit deeper, an analysis was made of the average travel times for the before and after situations (Fig. 76). Although based on a limited number of peak-hour runs on dry pavement the figure indicates that the saving in delay that resulted from the removal of STOP signs on Augusta was absorbed, for the most part, by increased delay at the signalized intersections with Ridgeland and Austin Avenues. In addition, it should be realized that the vehicle had to be completely stopped in order for it to register as such; therefore, the time spent creeping forward at STOP signs is not included under stopped-time delay.

The time saved on Augusta Street after removal of the three STOP signs amounted to about 40 sec on a 300-sec run, or an average of about 13 sec per vehicle per STOP sign removed. This saving was entirely on running time, and included deceleration and acceleration at STOP signs. The measurement "time slowed by STOP sign" refers to the delaying influence of the STOP signs. A significant difference was found in these data between before and after conditions.

Six runs were made before, and four runs after, the removal of STOP signs on all of the five S routes. The average values show, generally, slight decreases in brake application, speed change, and running time. However, there was a slight increase in direction change and a general increase in total time due to more stop time. This is probably the result of longer stopping time on the minor street at the newly installed two-way STOP signs compared to a relatively quick entry possible at the four-way STOP control previously present. Analysis of the north-south sections alone shows that stop time increased greatly on Oak Park, East, and Lombard Avenues, but not on Harlem and Elmwood Avenues. Therefore, the increase in stop time on the S route at Harlem and Elmwood was due to delay on the west-east sections of the route.

Quality of Traffic Flow Index

A quality of traffic flow index suggested by Greenshields (6.28 footnote) was used to obtain some preliminary estimation of the combined effect of these parameters. The index is of the form

$$Q = \frac{\text{Average Speed} \times 1{,}000}{(1 + \text{Change in Speed})\,(1 + \text{Change in Direction})} \tag{4}$$

in which Q is the quality of traffic flow index for a given section of roadway. This index was computed for peak period data on six major routes through the study site. The results are given in Table 6.

The rate of change of speed is expressed in miles per hour per minute of running time. The rate of change in direction is expressed in degrees per minute of running time. The factor of 1,000 was employed to bring the number to reasonable value.

The quality of flow indices fell between 1.7 and 7.8. There was an increase in Q from 5.3 to 7.8 on the route along the entire length of Augusta after the removal of the STOP signs. However, the full-length route along Division dropped at the same time from 3.3 to 2.6. All but one of the major S-shaped routes held about the same value for Q, before and after; the path involving Lombard Avenue showed a decrease from 2.2 to 1.7.

The percentage change in Q is shown for each route in Table 6. While the flow index on Division dropped 19 percent, the index on Augusta rose 58 percent. It is not readily explainable why the quality of flow index should become lower on Division, where no change was made. It is possible, however, that weather condition influences the traffic flow index. If it were assumed that Division represented a control section, the changes in the quality of flow indices could be related to a decrease of 19 percent as a base value. The result of this assumption is shown in the last column of Table 6. Augusta now shows an increase in quality of flow of 68 percent while three of the S-shaped routes show an increase between 13 and 21 percent. The only route showing a decrease is the S-shaped path using Lombard, due to larger waiting time to enter Augusta at Lombard at a two-way STOP compared to a four-way STOP. Its being greater here than at the other two points was probably due to the greater volume passing this point.

The change in the quality of traffic flow index corresponds generally to the change in route choice obtained in the questionnaire study. It is anticipated that future detailed studies of the system effects of control devices could be designed to test the correlation between route choice and a measure of the quality of traffic flow such as that discussed.

EVALUATION OF STUDY METHODS AND PROCEDURES

One of the major purposes of the pilot studies conducted during this first stage of research was to test methods of measurement and methods of study of intersection operation. The resulting experience was to serve as a guide in designing detailed studies during the second stage of the project. Work has already begun to evaluate fully the instrumentation, field study procedures, and parameters investigated for the purpose of organizing the next stage of research. Some tentative conclusions are given here as an indication of the general experience gained during the first stage.

Instrumentation

It was found that time-lapse photography provides an efficient tool for collecting data on a number of parameters of intersection operation. The accuracy attainable with the camera, through variation of filming speed, is sufficient for the purposes of the project. The major problem with the use of photography is to find sites which give suitable fields of view.

The 20-pen recorder can be useful in collecting certain data required on this project, but to perform the types of studies where the pens are to be activated manually, extensive equipment set-ups and field personnel are required. In these cases, other instrumentation could probably be found to make the study in a simpler manner.

The use of stopwatch and enoscope to obtain speed profiles and travel times was found to be a good method of measurement. The accuracy is limited, of course, by the observer's reaction time. It was concluded that the accuracy was within that desired for travel time studies and that it depended on the use intended for the speed determinations, as to whether this method had sufficient accuracy. Difficulties arose in the method of sampling when only one or two observers were used to obtain speeds over several "traps."

The major problems with instrumentation arose in connection with speed determination. The speed of 100 frames per minute does not allow accurate speed determinations from the films. Also, the stopwatch and enoscope method does not allow accurate determinations of speed over short traps. However, speeds could be taken accurately over short distances from films taken at a speed of about 300 frames per minute. Other instruments, such as radar, should be investigated for possible use.

The instrumented vehicle employed in gathering data on route characteristics and driver action is still in its developmental stages. In spite of this, it was found to be a useful device, because it measures parameters not heretofore easily obtained and provides the information with a minimum of field effort. The digital display and photographic recording mechanism produced some problems, which apparently can be minimized or eliminated in the future. Although a digital output is easier to process, an analog (e.g., graphical) output might be preferable for some of the measurements. An analog display provides a better check on the operation of the recording devices and gives an immediate picture of the results of each run. The disadvantage is that for mathematical analysis the results must be translated to digital form.

Questionnaires to obtain driver opinion and information about the driver's travel habits were found to be a very useful device. Depending on the amount of funds available, the nature of the study being made, and the situation in the field, the type of questionnaire can vary from a roadside interview to a mail-in questionnaire. The bias introduced in questionnaire sampling devices should be realized when analyzing the results. It was found that pretesting of the proposed questionnaire can avoid much misinterpretation of questions.

Study Methods and Analysis

As preparation is being made for the second stage of research, the field methods employed during the first stage are being reviewed and redesigned. One major consideration is the relative efficiency of combining the collection of most of the desired parameters into one integrated field study, as opposed to preparing separate field procedures to gather data on several smaller sets of the various parameters. It seems likely that the latter method would be a more flexible procedure, especially since certain parameters are measured with specific instrumentation. This would mean that each intersection would not necessarily be studied to obtain information on every parameter. In fact, different intersection conditions may be desired to study the variation of different parameters. The method of more individualized studies would then allow this more independent type of study of each parameter. Specific field procedures will be analyzed and redesigned as the specific objectives of the second stage are finalized.

More rigorous statistical sampling procedures can be employed, basing sample size requirements on the data obtained during the first-stage work. With larger sample sizes and a wider scope of coverage, more detailed mathematical analyses can be carried out to investigate correlations between parameters and factors causing their variation.

Data processing machines and computer analysis were found to be useful tools in the course of this study. The use of computer processing should be increased, as it gives flexibility to the analyses. It was found especially helpful in tabulating and analyzing data from the intersection film. Thorough investigation should be given to greater use of statistical testing programs. Also, consideration should be given to the utilization of a graphical output routine, as its time savings would allow a number of different approaches to be tried.

Parameters Studied

Each parameter chosen to describe some aspect of intersection operation has brought out some interesting aspects of operation under the different control conditions studied. It is indicated in the discussion under the recommendation for further study that most of the second-stage research should be devoted to the study of intersection operation toward the purpose of developing warrants for traffic

controls and in the evaluation of capacities. This will require classifying the parameters into two groups: (a) those directly usable in determining warrants, and (b) those of more theoretical interest. Those falling within the first classification will be studied in greater detail, whereas those in the second classification will be investigated further as time and funds permit. This classification is being carried out at present. It seems likely that gap and lag acceptance, delay, and safety characteristics should be included in some manner in the warrants to be developed. Other parameters will be chosen as deemed advisable.

Although many parameters of individual intersection operation were studied, the different aspects of each would not all be covered. Some discussion is included here of the suggestions for additional investigations of certain of the parameters studied.

For gap and lag acceptance, the difference between straight through, left-turn, and right-turn maneuvers should be investigated, as should the difference when the gap or lag is formed by near-side or far-side vehicles. Deceleration characteristics of the minor-street vehicles should be studied in detail within the section about 100 to 150 ft prior to the intersection and should be compared for the conditions with and without traffic on the major street. Investigation should be made of the number and types of hazardous maneuvers and near misses at an intersection under different controls. A more detailed study of driver obedience should also be made. In all cases the variation in these parameters as caused by the physical conditions at the intersection should be studied. Results of the first-stage work indicate the character of the intersecting streets and the sight distance restrictions to be two major factors.

As noted in the section on recommendations for further study, the study of effects of control devices on route operation will require an extensive period of review during the second stage before the best parameters and methods of study can be chosen.

CHAPTER FIVE

COMPARISON WITH PREVIOUS STUDIES

This chapter has been included to provide some continuity between previous work in the field of traffic control research and this project. The major purpose is to determine if the results of this project lead to conclusions similar to those of studies with comparable parameters. A similarity in results would provide support for the conclusions of this study because that would indicate reproducibility of the results for other locations. Inconsistency in results would prompt further investigation of the causes for difference, primarily to identify the factors which affect traffic.

Rather than cover every study which allowed comparisons, a review was made of studies most directly related to the purpose of this project. In a number of cases comparable data were not available on the type of information collected for this study.

INDIVIDUAL INTERSECTION OPERATION

Gap and Lag Acceptance

Raff (2.33) conducted a study of lag acceptance at several STOP-controlled intersections in New Haven, Conn., in 1950. The results of lag acceptance for two of his intersections are shown in Figure 77, with the corresponding curve for this project.

The definition of lag used by Raff differed slightly from that used in this study. He defined the arrival of the major-street vehicle as the time it reached a point opposite the curb line entering the intersection, whereas on this project the time of arrival was measured to the midpoint of the intersection. The difference means that lags measured by Raff are about ½ sec shorter than corresponding lags as measured herein. This assumption is based on an average minor-street width of about 30 ft, and a major-street vehicle speed of 20 mph. The curves taken from the data by Raff, therefore, have been shifted to the right by ½ sec to provide a more direct comparison.

Intersection A is in an industrial section and has buildings relatively close to the curb on all four corners. Intersection C is in a residential area, where the sight distance is much better than for intersection A. Information was not sufficient to quantify the sight restriction.

Two things are apparent from Figure 77. First, at the controlled intersections a greater lag acceptance is indicated for intersections A and C than for the intersections studied in this project. Second, intersection A, with greater sight restriction, shows a higher acceptance rate than intersection C. This is the opposite of the conclusions drawn in this study. Raff makes a tentative suggestion that "the side-street driver at an intersection of this (severe sight restriction) character is likely to accept shorter lags than he would want at an open type of intersection." Although a similar relationship was found for the study of gap and lag acceptance at the two STOP-controlled

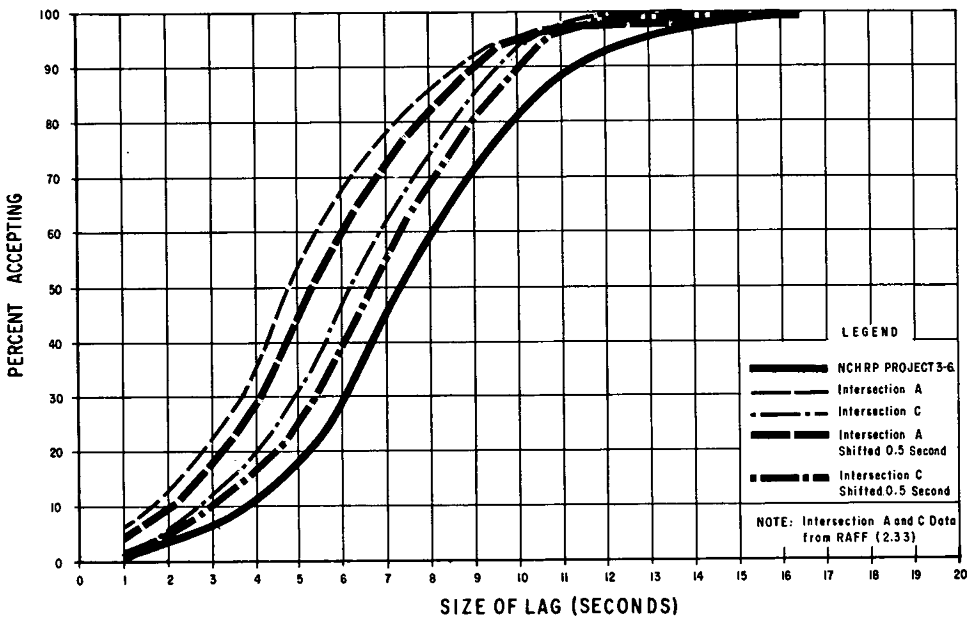


Figure 77. Comparison with Raff for lag acceptance under STOP *control, all intersections, combined peak and off-peak periods.*

intersections of this study (see Fig. 33), the sight restriction at Fifth and Linden was not excessive. In fact, the more logical reason for this occurring was given as the character of the major street relative to the minor street. Background information is inadequate for a similar comparison of the streets involved at intersections A and C. Quite possibly differences in the type of driver being measured caused the differences in results. In any case, this comparison indicates that more detailed study of the effect of sight restrictions and geographic location is warranted.

Swerdloff (2.38) studied gap and lag acceptance at two intersections in Skokie, the suburb where sites B and E (Fig. 3) were also located. Figure 78 compares the results of his study with those for the two STOP-controlled intersections of this study. Swerdloff's definition for arrival of the major-street vehicle was identical with Raff's. Because both gaps and lags were studied, however, a simple shift of curve cannot be made because the measurement of gaps is independent of reference line location. To this extent, therefore, direct comparison is limited. It is unlikely, however, that the resolution of the difference in definition would cause much change in the relative positions of the curves.

Niles Center Road is a four-lane major street at the intersection with Howard Street, whereas Howard Street is a two-lane major street at the intersection with Kostner

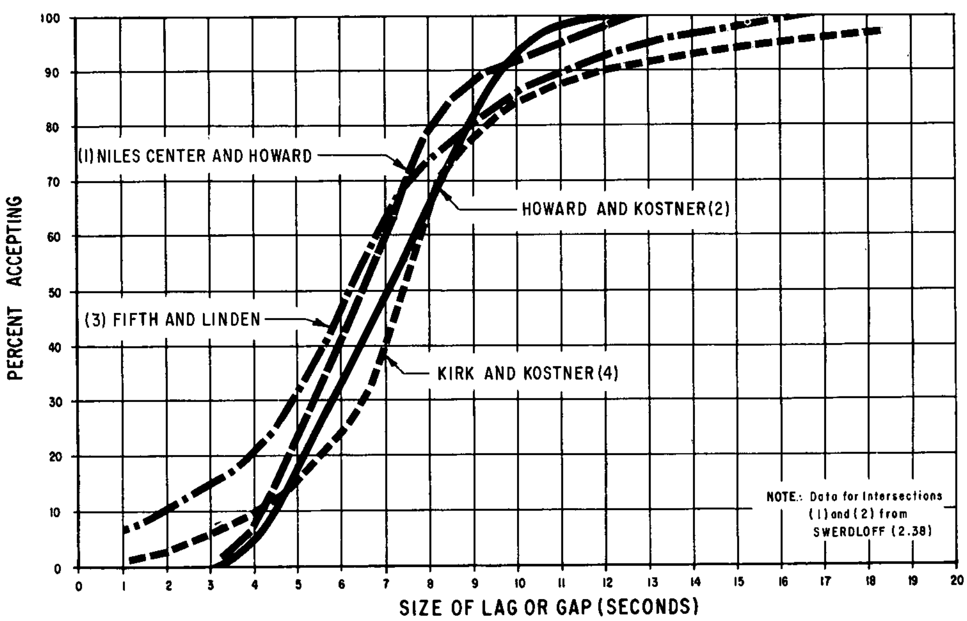


Figure 78. Comparison with Swerdloff for gap and lag acceptance under STOP *control, combined peak and off-peak periods.*

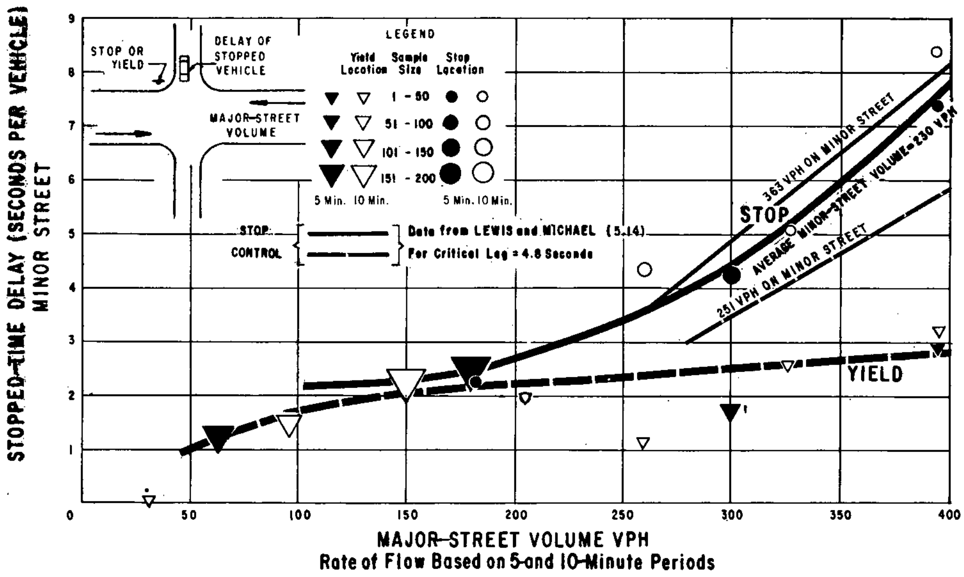


Figure 79. Comparison with Lewis and Michael for minor-street stopped-time delay by major-street volume.

Avenue. Both intersections are in residential areas and have good sight distances.

Figure 78, comparing results of the two separate studies, shows quite similar acceptance characteristics. It is interesting to note that the major streets, except for Linden Avenue, have a general character of priority, and the curves show lower acceptance than at Fifth and Linden for gap or lag sizes of less than 7 sec. This same relationship was pointed out for the study intersections of this project.

Greenshields (2.13), in his study of one intersection in New Haven, Conn., found 50 percent acceptance of gaps and lags of about 6 sec. The corresponding sizes were 6 sec at Fifth and Linden, and 7½ sec at Kirk and Kostner.

Inwood, *et al.* (1.10, 1.11) studied the behavior of vehicles emerging from the minor road at 13 sites where HALT (STOP) signs were replaced by YIELD signs. They found that there was 100 percent acceptance of gaps above 12 sec. They also concluded that the change from STOP to YIELD control did not affect acceptance characteristics except possibly for the left-turn movements, and that the type of intersection, rather than the type of control, seemed to affect the gap and lag acceptance characteristics. This has been suggested from the results of this study as well.

Travel Time and Delay

Because of the form of the data on travel time and delay in this study, it was possible to obtain only a few comparable results from other studies.

Lewis and Michael (5.14) and Kell (5.11) have published results of major simulation studies of delay at STOP-controlled intersections. It was not possible to compare overall delay results, but Lewis and Michael plotted data on the "average wait" of each vehicle. This differed from stopped-time delay only in that the time a minor-street vehicle in a queue exceeded a speed of 4.5 ft per sec (speeds blow 4.5 ft per sec were considered as stopped time) while moving up in line was included in the wait time. Because of the negligible amount of queuing at the volumes studied, it was decided that a comparison could be made. Portions of two curves given by Lewis and Michael have been plotted in Figure 79 with stopped-time delay results for this study. The results for stopped-time delay at the STOP-controlled intersections of this project represent an approximate average minor-street volume of 230 vph, compared to the simulation study volumes of 363 and 251 vph. Considering the differences in the study methods, reasonably close agreement is shown in this comparison. Future field studies could appropriately determine the extent to which minor-street volume affects intersection operation over a wide range of values.

Inwood, *et al.* (1.10, 1.11), in a study of 13 intersections in England which were changed from HALT (STOP) to YIELD control, found that delay was reduced with the change to YIELD signs. Delay was defined from a base travel time measured at the intersection when no vehicles were on the major street. The delay at the YIELD sign was 39 percent below that for the same intersection under STOP control. This reduction was statistically significant. Time required for straight through movements decreased from 3.3 sec under STOP control to 1.8 sec under YIELD control while (British) left-turn delays went from 2.3 sec under STOP control to 1.2 sec under YIELD control per vehicle.

Radelat * studied delay to minor-street vehicles on the east leg of Kirk and Kostner (site B). He concluded that delays on the minor street are lower with YIELD control than with STOP control, and estimated the reduction at about 17 percent. Estimates of delay were based on an

* Radelat, G., *Comparative Effects of "Yield" Signs and "Stop" Signs on Traffic Approaching a Through Street from a Side Street.* Unpublished Master of Science Thesis, Northwestern University, June 1964.

"ideal travel time" measured from runs with a test vehicle, by averaging the time to travel through an intersection with no traffic present.

Speed Profiles

The only information found on studies comparing speed profiles for YIELD and STOP control is given by Kell (1.13), who published the results of a study by a graduate student in San Francisco. The profiles show speeds beginning about 95 ft from the projected curb line of the intersecting street. The profiles for the current project follow the vehicle speeds up to about 100 ft ahead of the curb line. Detailed study was not accorded the last 100 ft. The study reported by Kell, therefore, gave an indication of what could be expected. The results showed that when traffic was present on the major street the profiles were quite close, with YIELD-controlled vehicles traveling slightly faster than STOP-controlled vehicles; the minimum speed was about 3 to 5 mph. When no major-street vehicles were present, the difference in deceleration characteristics became noticeable about 35 ft from the curb lines. The STOP-controlled vehicle decelerated to an average speed of 6 mph, whereas the YIELD-controlled vehicle proceeded at about 10 mph.

To investigate fully the deceleration characteristics at the various controls, the effect of sight distance should be studied. No information was available from the previously mentioned report by Kell on the type of intersection from which the data were taken. The more restrictive sight distance would probably tend to cause similar deceleration characteristics for each type of control.

Headway Distribution

Many researchers have studied the distribution of headways in a traffic stream under different conditions. The studies reviewed for the low-volume range studied on this project were all based on statistical approximations of Poisson's probability law. The "double," or "composite," exponential distributions proposed for use by Gerlough and Schuhl (6.43), Gerlough (5.55), Kell (10.53), Oliver (10.59), and others, were developed to include the effect of "restrained" vehicles at higher volumes under which some traffic cannot move freely. It was found that this refinement was not justified for the low volumes of this project.

All authors agreed that exponential distribution applies to arrival of vehicles in an undisturbed stream. However, the disturbance to a traffic stream caused by intervening unsignalized controls had not been studied in any systematic manner, thereby eliminating any opportunity to make comparisons. Studies have been reported, however, which demonstrate how the presence of a traffic signal causes formation of platoons separated by long intervals. This would represent one case of deviation from the random distribution. This same tendency toward bunching, in a more moderate manner, appeared in this study when considering arrivals from intersections upstream when the immediately adjacent intersection protected the approaching stream so as not to disturb the flow. No other information was found on deviations caused by traffic controls, especially at high crossing volumes. The results from this study indicated that the interruption of flow by STOP or YIELD control at the immediately previous intersection did not seem to alter the randomness of arrival.

Safety Characteristics

ACCIDENTS

Before-and-after studies conducted in the past indicate a reduction in the number of accidents where YIELD signs have been installed at previously uncontrolled intersections. Berry and Kell (1.02) referred to two studies: Oklahoma City showed a 9 percent decrease in accidents at 28 intersections; in Portland there was a decrease in accidents at nine intersections, no change at three, and an increase at two. Kell reported a study in Berkeley (1.13) where there was a reduction of 44 percent. A study in Providence (1.27) also showed a decrease after YIELD signs were installed. Comparable decreases in accident rates were also evident from studies basic to this report.

In the Berkeley study (1.13), at one intersection where the major volume was forced to yield there was an alarming increase in accidents. Yet at Kensington and Woodlawn, where the major flow was controlled in this study, there was an overall decrease in accidents. This could have resulted from drivers on Kensington, who naturally took precedence when the intersection was uncontrolled, creating an even greater hazard than after the control was installed.

OBEDIENCE

Rice (1.20), who originated the YIELD-type control, found that 12.6 percent of drivers at intersections observed in Tulsa disobeyed the YIELD-sign speed limit of 15 mph. In San Francisco 8 percent of all drivers at one intersection and 24 percent at another exceeded the 15-mph speed limit (1.13). The Illinois speed limit for YIELD signs is 20 mph. Consequently, the results in this report are not directly comparable, other than to note that only 1 to 2 percent violated the 20-mph YIELD-sign speed restriction when the minor flow was controlled, and that the disobedience rate was much higher where the major flow was controlled. Radelat * reported that 96.6 percent of the vehicles on Kirk Street (site C) confronted with traffic on Kostner Avenue actually yielded the right-of-way. The 3.4 percent of the vehicles on Kirk which violated the YIELD sign caused a reduction of speed of the vehicles approaching on Kostner.

STOP-sign disobedience at two intersections in San Francisco ranged from 44 to 49 percent when a speed in excess of 5 mph was considered a violation. Wilkie (2.40, 2.41) reported disobedience at a two-way STOP sign when the "rolling stop" was not considered in violation, averaging about 1 to 2 percent at a number of intersections in Cook County, Ill. This compares with about 5 to 10 percent found in Wilmette and Skokie.

Wilkie also reported disobedience to a full stop as high as 62 percent and an average of 20 percent after studying

* Radelat, *Ibid.*

42 two-way STOP locations in Cook County, Ill. Keneipp (2.22) found 29 percent disobedience to the full stop in Champaign-Urbana, Ill., while Hanson (2.16) found an average disobedience rate of 72 percent in the St. Louis area. The full stop was also violated freely in Wilmette and Skokie, ranging from 52 to 76 percent. At Kirk Street and Kostner Avenue (site C), Radelat found 74.6 percent of the vehicles on Kirk stopped at the STOP sign. This percentage conflicts with the data obtained by film interpretation. The difference probably results from definition and judgment used to determine a full stop. The film studies eliminated vehicles with any movement, however slight, from the full stop category. These slow-moving vehicles were tabulated in the 0- to 5-mph range. This permitted a flexible method of categorizing vehicles in various ranges of motion.

ROUTE OPERATION

The use of instrumented vehicles such as the Greenshields drivometer is of recent origin. No specific studies heretofore have attempted to correlate the type of control along a route with driver actions and vehicle motion. Several indices have been suggested by Greenshields (10.45 to 10.48), Platt (6.28) and Heimbach (9.08) for measuring the quality of flow along a section of road. Indications from these studies and this project are that an index might be useful in identifying the extent to which traffic control devices affect flow along a route.

Many techniques are used to assign traffic to a street network being tested. These techniques relate the volume of traffic on alternative routes to the travel time or travel distance. Some methods of assignment include other characteristics such as turn penalties or the translation of time and distance into cost. Nothing has yet been published on the use of more detailed consideration of driver behavior characteristics in assigning traffic between alternative routes. Heimbach (9.08) states, in connection with a study of traffic generation to supermarkets, that "driver actions are a more precise measure of effective distance in the discounting relationships than either time or distance is for functional accessibility . . . " However, he did not attempt to correlate driver actions and route choice. The preliminary studies of driver behavior, however, seem to indicate useful applications to the study of the effect of traffic controls on route choice.

CHAPTER SIX

SIMULATION

To evaluate fully the effect of a traffic control device, it would be desirable to test it under a wide variety of conditions. It would be of further benefit to control certain parameters while holding others constant, thereby permitting conduct of experiments similar to those in the laboratory. It is not practicable, however, for the traffic engineer to study operation under such controlled conditions. Therefore, he must turn to methods of analogy, or modeling. It would help in analyzing intersection control to develop a model of an individual intersection or street system which would be sufficiently accurate in describing the operation to be able to determine the limiting and optimum operating conditions for the various controls under study. Such an approach is necessary because of the complex situation existing at an intersection where several traffic streams and a wide variety of complex variables are in constant interaction.

The use of a model in engineering analysis is not new, models having been used in one form or another for many years. These include physical models, analog models, and symbols or mathematical models. The development of mathematical models has been quite rapid since the development of the high-speed computer, and a variety of applications has been found: models have been developed to aid in designing automobiles, bridges, highways, and buildings. Furthermore, the use of the mathematical model seems well-suited to the analysis of traffic situations. When the mathematical model is used to describe the physical situation, it is often termed the process of "simulation," which is defined by the dictionary as "an imitation." Simulation of an intersection implies imitating the operation of that point in a highway network. Nevertheless, an imitation does not usually have all the characteristics of the object imitated, and this is true for the simulation of an intersection. The model should be designed, however, to include all those factors which play a significant part or which have a significant meaning in the operation of the intersection.

The mathematical model, by its very nature, usually requires a large number of repetitive operations to carry out the evaluation. The calculations could not be done manually as a practical matter. However, the development of the high-speed computer made such a method feasible. A high-speed computer, in fact, can simulate a complex traffic situation in much less time than the situation being represented would take.

THE SIMULATION PROCESS

The simulation process can be outlined as a series of four major steps, as follows (5.71):

1. Definition of the problem and the objectives of the model.
2. Formulation of the model.
3. Testing of the model.
4. Determination of the values of the parameters of operation to be used.

The definition of the problem should be made after careful consideration of the scope of the system to be studied and a comprehensive review of all factors involved. This is necessary so that the model developed will be flexible enough to handle all conditions which might occur. The model itself need not be designed to describe the entire operation of the system. It is necessary, therefore, to fully define the scope of the model. This should be determined by considering that portion of the system which justifies simulation.

Having defined the problem and the scope of the model, the next step is to determine the criteria which will be used as yardsticks in analyzing the system operation. This must be done before the model itself can be completely formulated, and is one of the most important steps in the simulation process. The criteria designated here are the ones which will be used to measure the relative levels of operation under different design or traffic conditions. They should be measurable quantities which effectively describe the system operation in some quantitative manner.

In formulating the model, the engineer must be careful to express the interaction of each of the elements of the system which affect the parameters being used as criteria. The actual model is compiled in four steps, as follows:

1. Determining the physical characteristics of the system and expressing them in mathematical form.
2. Expressing the operation system in a series of mathematical routines describing the interaction of each of the factors involved.
3. Determining the inputs and outputs desired from the model.
4. Quantifying the parameters to be used in the computational procedures of the model.

The physical system can vary. Therefore, the model should permit revision of the system with minimum effort. The routines must allow the system operation to be programmed and simulated on the computer efficiently. The inputs required will follow from the first two steps of the formulation process. The outputs desired will depend on the criteria chosen to analyze the system. Quantification of the parameters is a most important part of the simulation process. However, traffic engineers have little information on this subject. The usefulness of the model depends on the accuracy with which the various parameters are described.

When the model is formulated and the traffic engineer is satisfied with the accuracy of the parameters being used, he is ready to test the model. The testing is done in two steps. First, a test run is made on the simulation model for a given set of conditions in the system. The realism of the model can be tested in a general way by observing whether or not the outputs are reasonable. Second, a more exacting test can be applied by simulating conditions for an actual location. The accuracy of the model can then be tested by comparing the output of the simulation with field measurements of the same parameters. This leads to an iterative process whereby the model is made successively more accurate.

Once an accurate model has been developed, the engineer has a useful tool to test any number of alternative designs. The model can be used in determining overall policies as well as in evaluating proposed designs.

SURFACE STREETS AND AT-GRADE INTERSECTIONS

Mathematical models have a number of applications in traffic engineering. Digital computer simulation methods have been under development for more than 20 years. The methods have been applied to analysis of at-grade intersections, sections of freeway and surface streets, and arterial networks. The application has varied from the macroscopic traffic assignment model on the one hand, to the detailed intersection operation model on the other.

The development of simulation models of at-grade intersections and surface streets began about 1956 (5.05). The first attempt was somewhat crude due to oversimplification, but it was the pioneering effort in an approach which has matured quite rapidly. There are a number of models in use at present. Some simulate a section of a street; others, a network of surface streets; still others attempt to describe the operation of a single intersection in detail.

This project is seeking to determine how certain regulatory devices affect capacity and operation at a given intersection and throughout an entire street system. The need to describe effects under a number of conditions indicates the desirability of the simulation approach.

It was decided, therefore, that a review should be made of the possible applications of the simulation process to this project. Accordingly, a number of the existing simulation models were analyzed as a portion of the review. Information was taken from the various publications describing the models (see Appendix C, Section 5) and the models were compared in the areas of general objectives, general characteristics, inputs, outputs, and model operation. In many cases, sufficiently detailed information of the same type for each model was not readily available.

Most of the work which has been done on intersection simulation and surface street simulation was begun in 1956 by Goode, Pollmar and Wright (5.05), who reported development of a simulation model of a signalized intersection. Wong (5.72), also in 1956, reported the simulation of a twelve-lane, two-way boulevard section. These studies represented a pioneering effort in the construction of a digital computer simulation model and were therefore quite simplified.

Benhard (5.02), Lewis (5.12) and Jorgensen (5.08) later developed more sophisticated models. New models and recent advancements have been recorded by Kell (5.09), Lewis and Michael (5.14), Stark (5.20), Ger-

lough and Wagner (5.04), Aitken (5.01), Ruiter and Shuldiner (5.18), Miller (5.15), Snell (5.19), and Morrison and Moores (5.16). The recent advancements in simulation include simulation of a nine-block city street system by Stark; simulation of an at-grade intersection using distributions to describe arrival rates and driver behavior characteristics by Kell, Lewis and Michael, Aitken and others; and simulation of a highway network by Gerlough and Miller. Ruiter and Shuldiner have modified the Lewis and Michael model to include a method of computing operating costs.

SIMULATION ON CURRENT PROJECT

The objective of this project in the area of simulation is to develop a model with sufficient accuracy to describe the operation of a system under a number of controlled conditions. The ultimate goal is to be able to describe the effect of regulatory devices in a given system so that the application of these controls may be made in such a manner as to optimize the operation of that system.

The simulation model that will be developed for use on this project should meet certain requirements based on a set of general criteria. The word "model" as used here could be construed to mean one or more simulation models, because it might be advantageous to have separate ones for investigating street system operation and operation at an individual intersection. The following criteria, based on particular requirements and objectives of this project, have been established:

1. General Criteria
   (a) The model should be flexible enough to allow variation of physical, control and operational conditions with a minimum effort.
   (b) The model should realistically and accurately simulate system conditions for the purposes of this project. This will require the use of stochastic models to describe operational and driver behavioral variations at an intersection.
   (c) The model should exclude refinements which do not add significantly to accuracy.
   (d) The model should be designed to use computer time efficiently.
   (e) The input should be based on operational patterns and characteristics which can be readily measured and checked.
   (f) The output should be designed to allow testing and analysis in the simplest possible manner.
   (g) The amount of data and its processing for a particular investigation should be minimal (5.01).
2. System Criteria
   (a) The model should be flexible enough to describe operation in a system of streets for any particular vehicle, as an average per vehicle, or as a total for the system.
   (b) The model should be sensitive enough to show operational variation with a significant alteration at any one point in the system.
3. Individual Intersection Criteria
   (a) For defining operation at an intersection the model should be so refined as to describe in detail the effect of system changes on driver behavior characteristics.
   (b) Operational rules should be of sufficient detail to be sensitive to changes in control, physical, or driver behavior conditions.

The purpose of this review of simulation studies is to choose several for more detailed analysis and experimentation at a later stage of the project. The intention is that the detail study would reveal those characteristics which would be desirable for inclusion in a model designed for the purposes of this project. The next step would then be either to modify one of these models or to develop a new model which contained each of the desired characteristics. The models designated hereinafter for further study have been chosen on this general basis.

During the review of published work on simulation it became apparent that rather than any one, or a few, of the models being preferable for further analysis, several had desirable characteristics or methods of handling a specific aspect of the process which were worth further analysis. Some of the major items have been summarized as follows for further consideration during the detailed analysis suggested for a later stage:

1. Individual Intersection Models
   (a) *Arrival Rates*—Kell (5.09) has used a composite exponential function, as suggested by Gerlough (5.55), to calculate arrival headways. A Monte Carlo technique is used in the generation process. Aitken (5.01) reports use of the exponential function for constrained vehicles as developed by Gerlough, also generating arrivals with a Monte Carlo technique. His model generates the vehicles and queues them at a signal upstream from the intersection being simulated. They are released on the green and then translated into an arrival rate at the intersection being simulated downstream, using the same distribution for constrained vehicles but with a different minimum headway value from that used for arrival at the signal. In this manner the effect of a signal or other control upstream can be determined.
   (b) *Gap and Lag Acceptance Characteristics*—Kell (5.11) has used a log-normal distribution to describe headway acceptance characteristics. He based this choice on a study performed by Bissell. Acceptance characteristics differed for each turning movement. The acceptance or rejection was determined with a Monte Carlo technique. Snell (5.19) ran an experiment on a simplified model which showed that the use of a distribution for describing acceptance characteristics provided a much more realistic representation than using a single "critical" value.
   (c) *Car Following*—Work is being done at Ohio State University to simulate the car-following situation on a digital computer (5.49). Lewis and Michael (5.14) have used the car-following equation to govern vehicle speed and spacing in their simulation model. This would seem supe-

rior to use of a constant minimum vehicle headway and a limited step-function speed curve.

(d) *Other Operational Characteristics*—Several other specific characteristics which seem desirable appear in varied form in a number of existing models. They include:
   (1) Random assignment of turning movements at the generation point with check points to allow turning vehicles to position themselves, in advance, for the turn;
   (2) Lane changing allowed on multi-lane models;
   (3) Passing allowed on the approach or at the intersection where turning vehicles are waiting to complete their turns;
   (4) Sufficient length on each leg to describe fully the approach and departure characteristics; and
   (5) Retention of the individual identity of the vehicle and its operation.

(e) *Output*—The output of a simulation program is usually quite specialized, being designed to meet the specific needs of the project. Certain parameters are determined in most models, whereas others appear in only one case. The desirable contents of a program output include:
   (1) Volume, in vehicles per hour;
   (2) Directional distribution of vehicles;
   (3) Turn percentages;
   (4) Real time simulated;
   (5) A number of values measuring delay;
   (6) Queuing and storage characteristics;
   (7) Headway distributions;
   (8) Speed distributions; and
   (9) Costs.

2. System Simulation Models

(a) *System Configuration*—Gerlough and Wagner (5.04) reported simulation of an entire network of arterial streets with right-angle and oblique intersections. Stark (5.20) has simulated a nine-block section of a one-way city street with right-angle and oblique intersections. A model which simulated a network of fair size would be preferable because various routes within the system could be analyzed, as well as the entire system. However, other desirable features should not be sacrificed in order to increase the scope of the system.

(b) *Controls*—The nine intersections simulated by Stark (5.20) consisted of three STOP-controlled intersections and six signalized intersections. The models used by Gerlough (5.04), Rhee (5.17), and Godde and True (5.07), have only signalized controls. However, because this project is concerned with control devices it is particularly necessary to be able to test any combination of various types of controls in the system.

(c) *Vehicle Identity*—Stark (5.20) and Wong (5.72) hold the identity of individual vehicles in and passing through the system. Gerlough and Wagner (5.04) and Rhee (5.17) describe system operation only and do not retain individual vehicle identity. Although recording vehicle identity is less efficient in terms of computer time, it is desirable at this stage of the project to be able to analyze and categorize individual vehicle operation. The amount of information retained on each vehicle should be determined after more detailed review.

It would be useful to be able to include an optical output routine so that the resulting simulations could be viewed and photographed. It would also be advantageous to have a graphical output routine so that the values could be plotted and recorded in tabular form.

The model should be formulated so that the system designation could be varied for analysis of one-way and two-way streets, varying number of intersection legs, varying controls, varying geometric conditions, etc. Investigation could then be conducted to determine effects of sight distance, lane widths, street widths and other physical features on the parameters of operation.

This represents only a few of the many aspects of the simulation model. It would be advantageous to experiment with one or more of the available models as work continues on the project. This would increase familiarity with the mechanics of the simulation process as well as aid in decisions concerning the characteristics of the final model. The ones which seem best suited for such experimentation are those developed either by Kell or by Lewis and Michael for an intersection, and that developed by Stark for a street system.

CONCLUSIONS

The use of a simulation model to study the effect of regulatory devices on operation of a given system would be of great value in extending the results of field studies and in refining warrants as they are developed. However, the model should be developed only after sufficient study of the problem as it exists so that the situation will be understood fully enough that conditions can be simulated accurately. Not only will this understanding be ample, but there will be available a store of quantitative data describing operational parameters required in formulating the model. This is the most important portion of a simulation study. The investigator must not give way to the temptation to use just any available data, making assumptions and modifications to fit his model. The accuracy of the results will depend on the accuracy of the basic data.

The actual programming and testing of a model is costly in both time and money. It is, in fact, almost a project in itself. It is given over to developing routine and subroutines, preparing inputs, and designing outputs. The preparation also includes testing and correcting, checking, and rechecking.

The program for developing a simulation model was begun by reviewing existing work on this subject and considering applicable models for further study. The next step is under way. Field studies are being conducted to investigate effects of control devices at existing locations. Data are also being collected on traffic characteristics and driver behavior. Although these data are being used to

analyze operation and to develop warrants, they will also be useful in quantifying operational parameters required in the simulation model. This work will be continued during the later stages of the project.

It is suggested that the actual outline and programming of the final model be deferred until sufficient information and insight are attained so that these steps can be formulated on a sound basis. In the meantime, however, it might be advisable to conduct limited experiments with applicable models as suggested in the foregoing. The results of the experiments could be checked against field data from the project studies.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

The conclusions that follow are based on the results of the pilot studies. Statements are made concerning the two general points of interest for this stage of the research: (1) preliminary relationships concerning operational characteristics, which were based on indications from the data and developed as guides for further study; and (2) conclusions on the effectiveness of the instrumentation, the field methods, and the parameters employed.

The intersections studied are all located in the Chicago metropolitan area and therefore represent operation only for the traffic ordinances enforced locally. Being within an urban street system, they do not include operation under isolated rural conditions. The volume of traffic on major or minor streets of the study intersections did not exceed a two-way total of 400 vph. The total intersection volumes varied between 150 and 550 vph. Speed limits were 25 or 30 mph on the approaches, and generally averaged about 25 mph through the intersection along the major street.

The results represent a sampling of limited size and a somewhat limited scope of conditions. The studies have served their purpose well, however, by providing valuable information to guide the development of integrated theory on unsignalized intersection control. They will also be fully used in the design and completion of detailed studies to be carried out during the second stage of this research.

CONCLUSIONS ON OPERATIONAL STUDIES

Gap and Lag Acceptance

1. The gap or lag acceptance for sizes above 20 sec is about the same for YIELD-controlled as for STOP-controlled intersections. (All of the following conclusions that make reference to gap or lag sizes pertain to those below 20 sec unless otherwise noted).

2. Indications are that the driver on a minor street controlled by either a STOP or a YIELD sign reacts differently when considering the initial opening (lag) available to him than when considering the following openings (gaps), having rejected the first one.

3. There seems to be a greater probability that a driver at a YIELD sign will accept a given size lag than if he were at a STOP sign. However, having rejected the lag, the driver at a YIELD sign is less likely to accept a given size of gap which follows.

4. Variations in specific intersection characteristics tend to cause as much variation in gap and lag acceptance characteristics as the type of control used.

5. The character of the major street tends to affect acceptance characteristics. That is, the less priority the major street has, in the opinion of the minor-street driver, the greater the probability of his accepting a gap or lag of a given size.

6. There is some preliminary indication that the volume and speed level on the major street have some effect on the acceptance characteristics under YIELD control.

7. Reducing the sight distance at a YIELD-controlled intersection tends to lower the probability of acceptance, especially when the view is so limited that the safe approach speed falls below the legal approach speed for the YIELD sign.

8. The middle range of gap and lag sizes for both YIELD and STOP control, between 15 percent acceptance and 85 percent acceptance, is approximately from 3 or 4 sec to 10 or 11 sec. The 50 percent acceptance generally occurs at about 6- or 7-sec sizes.

9. The relative gap and lag acceptance characteristics tend to vary between peak and off-peak periods for both YIELD and STOP control.

Delay

10. The average overall delay to minor-street vehicles, for the volume conditions studied, at an intersection with YIELD control was less than that at the same intersection with STOP control. The difference in delay between the two controls varied from about 3 sec with almost no major-street traffic, to about 2 sec with a rate of flow of 300 vph.

11. The amount of overall delay for each type of control rose about 1 sec for each 100-vph increase in traffic on the major street.

12. The average stopped-time delay to minor-street vehicles at the major-street rate of flow between 100 and 200 vph is about 2 sec for both YIELD control and STOP control. At higher major-street volumes the stopped delay for YIELD-

sign control rose slightly to about 3 sec, and for STOP control increased much more rapidly to about 8 sec at a rate of flow of 400 vph on the major street. For this condition, therefore, there is a stopped-time delay of 5 sec per vehicle greater with STOP control than with YIELD control.

13. The increase in the minor-street vehicles that were forced to stop by major-street traffic when YIELD control was changed to STOP control at a study intersection was found to vary between 6 and 13 percent for major-street volumes between 100 and 350 vph.

Speed

14. The type of control (STOP, YIELD or uncontrolled) appears to have little effect on the approaching speeds of vehicles on the minor street up to a distance of about 100 ft in advance of the control, although in both cases the vehicles normally are in the process of decelerating at this point.

15. Vehicles on the minor street start to decelerate about 200 ft in advance of the control sign and return to their normal speed about 200 ft beyond the control sign. This means that the effect of a control on the speed of approach at an adjacent intersection is normally negligible where speeds of 20 to 25 mph are maintained on the minor street and the intersections are spaced about 400 ft apart.

16. Turning vehicles on the minor street tend to reduce speed more than straight through vehicles when the intersection is uncontrolled. As control becomes more restrictive, however, this difference tends to disappear.

17. The average speed of the decelerating minor-street vehicle within a 100 ft "trap" just prior to the control location is of the order of 15 mph for each of the uncontrolled, YIELD, and STOP conditions. Where any of these vehicles is required to stop at the intersection, rapid deceleration apparently takes place within the last 50 to 75 ft.

18. The type of control does not have any effect on the approach speeds of major-street vehicles at 200 ft or more in advance of the intersection. The difference in effect on speeds on major streets between YIELD and STOP control is small, but the uncontrolled condition causes a more marked reduction. Indications are that the more positive minor-street control causes the major-street driver to decrease speed less across the intersection.

19. Sight distance restrictions play a significant part in determining speed patterns on the minor street.

Headway Distribution

20. In general, neither STOP nor YIELD control at an intersection rearranges the headway distribution on the minor street in any but a random manner, at the volumes studied.

21. The arrival rate of vehicles from all types of previous intersection control conditions studied can be closely approximated by the exponential distribution based on the law of Poisson.

22. Although it occurs in a random manner at each, the magnitude of rearrangement of headways is greater at a STOP control than at a YIELD control.

23. Vehicles arriving at an intersection from a previous intersection which gave the arriving stream priority, tend to platoon. If the previous intersection controlled the arriving stream in some manner, the smaller headways were spread due to impedance of the previous control, producing a more random arrival.

Safety

24. The annual accident rate tends to decrease after YIELD signs are installed at previously uncontrolled intersections. There is a temporary period of major reduction in accidents, followed in a year or two by a rise in the rate to some level below that which existed for the uncontrolled condition.

25. At uncontrolled and YIELD-controlled intersections where the lighter volume is controlled, the conditions under which there was the highest frequency of accidents during this study were (a) daylight hours; (b) wet, snow-covered, or icy pavement; and (c) poor sight distance combined with high approach speeds.

26. Where the YIELD sign controls the heavier flow, the intersection seems to be more accident prone under good driving conditions than where the YIELD sign controls the lighter flow. The installation of a YIELD sign against the heavier flow at a previously uncontrolled intersection, however, tends to reduce accidents.

27. Peak-period drivers on the minor street are more aggressive when an intersection is uncontrolled than when it is under YIELD control.

28. At YIELD-controlled intersections the rate of disobedience to the maximum legal entrance speed upon entering the intersection (20 mph in Illinois) is low (1 to 2 percent) and relatively constant when the volume of the protected street is greater than or equal to the volume of the controlled street. When the volume on the controlled street is greater than that of the protected street, however, the disobedience rate rises markedly (13 to 31 percent disobedience) as imbalance in volumes increases.

29. For the peak hour, when about 35 to 40 percent of the minor-street traffic at a STOP sign is forced to stop by the presence of traffic on the major street, a relatively small number of vehicles (about 1 to 9 percent) come to a voluntary full stop. The majority of the vehicles (47 to 57 percent) proceed through between 0 and 5 mph, while a small number (5 to 6 percent) proceed at more than 5 mph. During the off-peak period, when about 20 to 30 percent are forced to stop, the same general relationship holds (3 to 12 percent voluntary stops; 48 to 74 percent between 0 and 5 mph; 2 to 10 percent above 5 mph).

Route Operation

The following conclusions refer to a study of operation along a 1½-mile corridor located in a suburban residential area, including route choice of drivers moving through the corridor before and after a set of control changes along one of the two major streets in the system. The streets are generally two-lane, two-way, with parking permitted on both sides. The volumes on the two parallel major streets running the length of the corridor are on the order of a two-way flow of 400 to 700 vph during the morning peak hour.

30. Removal of three STOP signs along a 1½-mile length of roadway decreased delay, speed changes and travel time along the route.

31. The quality of flow index increased significantly with the removal of three STOP signs along the route.

32. Although operational characteristics as a whole were significantly improved along the two major routes as a result of changes from four-way to two-way STOP control, added delay of vehicles entering or crossing the major routes at these intersections was experienced.

33. Removal of the three STOP signs along the route caused a relative shift of about 8 percent of the total corridor traffic from other routes to an improved route. This was affirmed by driver statements to this effect.

34. Excluding "captive" drivers who logically would not shift from one route to the other regardless of the improvement because of adverse travel distance, the shift of those drivers who had a choice resulted in a net transfer of 25 percent to the improved routes.

35. The decrease in the amount of delay due to removal of the three STOP signs along the 1½-mile length of road came to about 13 sec per STOP sign per vehicle.

36. An even greater benefit in the form of reduced delay could have resulted from removal of STOP control if it had not been that some of the delay was transferred to the several signalized intersections along the route.

CONCLUSIONS ON STUDY METHODS AND PROCEDURES

1. Time-lapse photography was found to be an efficient and sufficiently accurate tool to collect data on a number of desired parameters. It will be useful for the second stage of the research.

2. The usefulness of the 20-pen recorder studies was found somewhat limiting during the first stage, but could be well applied in specialized studies that might arise during the second stage.

3. The use of stopwatch and enoscope measurements was found sufficiently accurate for the results desired during the first stage. This method of speed determination will need to be supplemented with other techniques where more accurate measurements are required, particularly in deceleration and acceleration studies.

4. The instrumented vehicle was found very useful in conducting studies of route characteristics and driver behavior. Further use will be made of such a vehicle when system studies are resumed. The digital output could well be supplemented with an analog output.

5. The mail-in questionnaire was found to be a very effective method for obtaining data on driver habits, desires and opinions.

6. Computer programs for the processing of data add significantly to efficiency and reduce time-consuming operations. Use of data processing techniques will be pursued and extended.

7. Use of an integrated study procedure which provided data on most of the parameters desired was found to work well for this stage of the research. Future studies will be more detailed, however, and it may be more efficient to conduct independent studies of several smaller sets of related parameters.

8. Each parameter studied has brought out some interesting aspects of operation under the different control conditions. As research proceeds, those parameters which are of specific use for the purposes of the second stage will have to be chosen and concentrated on, while the remainder will be studied further as time and funds permit.

RECOMMENDATIONS FOR FURTHER STUDY

It has been pointed out several times in this report that one of the major purposes of the first stage of research was to test methods and investigate results in order to develop a sound program for detailed study of the effects of traffic control devices on operation during the second stage.

Work is presently under way to fully evaluate the procedures and results for the purpose of designing the detailed studies for the second stage. Some indication of the conclusions being drawn from the first stage were made in previous sections of this report. Portions of the general recommendations for further study that were proposed, and generally approved by the NCHRP, are given in the following.

Objectives

The recommended general program was developed so as to accomplish two important objectives:

1. To provide the field of traffic engineering with some substantive material concerning individual intersection control at the earliest possible date. This information could then be applied in developing improved warrants for traffic controls and methods for evaluating capacities.

2. To allow time to completely review the results of the first-stage study of system effects, and provide the necessary time for extensive preparation required for a complete study. Conducting the work in this manner would eliminate wasted effort that might possibly arise from hurried progress into a relatively untried area.

Individual Intersection Studies

A major study of two-way STOP-, four-way STOP- and YIELD-controlled intersections will be conducted. Of the field work required during this stage, the individual intersection studies will constitute the primary effort. It is intended that the results of additional studies, when combined with first-stage results, would provide sufficient data to enable development of a concrete set of relationships concerning operation under these various controls. The methods of study would be much the same as those used in the first stage. Improvements in methodology will be made, and more comprehensive data will be taken where experience on first-stage research indicates the need to do so. The study will be more detailed in analysis and broader in scope of conditions. In all cases, analyses will be designed so as to produce immediately usable results in development of warrants for traffic controls and in evaluation of capacities.

System Studies

This area of study will consist of an effort to formulate and report a comprehensive definition of the scope and nature of the problem of system effects of traffic control devices. This will include (a) a development of theory concerning these effects, using results from the first stage to illustrate preliminary relationships; (b) a set of suggested methods of study; and (c) a description of the types of sites considered most fruitful for obtaining the various effects hypothesized. In preparation for this more comprehensive system study, several suitable sites will be investigated and arrangements made to have the necessary instrumentation available.

APPENDIX A

STUDY METHODS AND SITES

INSTRUMENTATION

Three general types of instrumentation—manual, photographic and instrumented vehicle—were used to gather field data for this study.

Manual

Manual studies included all data collection requiring personnel to measure and record data directly in the field.

VOLUME COUNTS

Turning-movement counts were taken manually at each study intersection during the periods of analysis. No machine counts were made. Counts were recorded by 5-min periods while speed profiles and travel time data were being collected. The counts were taken continuously from 7:00 A.M. to 6:00 P.M. except for a 45-min midday break. This information was used for determination of the average daily traffic, in addition to comparisons with speed and travel time data. It was also used to determine short-period volumes for correlation with travel time studies. Volumes were obtained from intersection films in connection with delay and gap acceptance characteristics, as well as to measure accurately the volume level during each filming period. Supplementary counts were made at several intersections adjacent to the study locations. During the route study, volumes were taken at the three intersections where the STOP signs were to be removed from Augusta, as well as at the intersections of these same streets with Division. In addition, counts were made during the questionnaire phase at the distribution points.

ENOSCOPES

These are L-shaped boxes, open at both ends, containing a mirror at a 45-deg angle. This arrangement bends the line of sight of the observer so that it is perpendicular to the path of a vehicle as the latter passes a pre-selected point. The 10 x 12-in. mirrors allowed satisfactory observations to be made at distances up to 450 ft. Travel times through each intersection were obtained by the use of stopwatches and enoscopes. One enoscope was placed on each leg of the intersection at a point in advance of where the vehicle was first affected by the intersection. The elapsed time between the point of entry and point of exit was taken by stopwatch and recorded on a form along with clock time. Each sample was then correlated with 5-min volumes counted simultaneously. The distance from the curb line of the intersection to the enoscope was measured. This permitted a comparison of before and after travel times. Filming was done during some periods when travel times were being recorded. The presence of these devices seemed to have little influence on driver behavior.

Speed profiles also were obtained by the use of stopwatches and enoscopes. The enoscopes were placed in a row at measured distances along one leg of the intersection, forming a set of "traps." Vehicles were timed between successive enoscopes and the number of seconds recorded. Vehicles entering and leaving the intersection on each leg were studied. The enoscopes were moved frequently from one leg to another in order to give a representative sample for each leg during peak and off-peak periods. These data were never taken while filming was under way. Therefore, any effect on driver behavior caused by using closely-spaced enoscopes was not transferred to the film studies.

20-PEN GRAPHIC RECORDER

An Esterline-Angus graphic time recorder was used as an experiment at Kirk and Kostner (Radelat).* In this machine a roll of recording graph paper moves past a bank of 20 pens at a constant speed. When a speed of 11.6 in. per minute is used, a roll lasts about 100 min. Each pen is connected to a separate telegraph key; when a key is depressed, the corresponding pen makes a mark on the moving paper. Thus it is possible to record simultaneously as many as 20 different operations. The various keys,

* Radelat, *Ibid.*

which can be placed hundreds of feet from the machine, are connected to the machine by electric cables.

The recorder was used to obtain speed profiles, travel time, and headway acceptance characteristics. Speeds and travel time were obtained in much the same manner as with stopwatches, the difference being that the observer pressed designated buttons operating the pens when vehicles passed each point, instead of starting and stopping watches. Headway acceptance was obtained by actuating a button each time a major-street vehicle passed a point on the pavement. Other buttons were actuated when side-street vehicles arrived and when they accepted or rejected the headways or lags. After experimenting with the recorder, it was decided that it was not the best possible method because it required a large field crew as well as wires across the roadway. Both of these constituted forms of marginal friction which influenced operating characteristics.

Photographic

Photographic studies were conducted using time-lapse cameras. The cameras were Keystone model A-9 "Criterion" 16-mm motion picture cameras, modified to be driven by interchangeable synchronous motors which maintain a constant frame interval at 60 or 100 frames per minute. During this study all films were taken at the speed of 100 frames per minute. The constant filming rate provided a time reference and made it possible to obtain about 40 min of usable film with each shooting. Use of a 15-mm wide-angle lens permitted a better view of the cross traffic when the camera was fairly close to the intersection. The cameras were mounted on a ball joint attached to a metal bracket that could be strapped to any pole or tree providing a good vantage point. In all cases the power source was a 12-v battery-inverter combination which produced a 110-v alternating current. Precautions were taken to insure that the camera operated at the correct speed. Points were painted on the pavement for use as spatial references. Use was also made of physical features as reference points.

In general, peak periods were filmed without stopping the camera. This provided a continuous record of approximately 40 min for each 100-ft roll of film. Due to the inherently low volume conditions at the study intersections, off-peak periods were generally filmed intermittently by operating the camera only when minor-street vehicles were approaching the intersection. The length of each filming was sufficient to display events at the intersection before and after the arrival of the minor-street vehicle.

The films were taken of intersection operation to obtain gap and lag acceptance, headway distributions, intersection speeds, volumes, potential hazards, and stopped-time delay.

Instrumented Vehicle

An instrumented vehicle employed for the route study was loaned to the project by its developer, Dr. Bruce D. Greenshields. Called the "drivometer and traffic events recorder," the equipment gives digital recordings integrated over any selected time or distance. Instruments attached to the vehicle measure driver actions and vehicle motions. Driver actions recorded included motions of the steering wheel, accelerator, and brake. Vehicle motions measured were speed and direction change. Traffic events were recorded by an observer who sat opposite the driver and operated a set of switches to record changes in the traffic situation. Counters connected to each switch are mounted on a display panel. A 16-mm movie camera is used to record the readings at designated intervals of time and/or distance. Traffic events recorded on this project were marginal friction, pedestrians, vehicles ahead, parking vehicles, cars approaching at an intersection, cars approaching from opposing lanes, and slowing by cause. Two drivers were used for the route study, the task being divided between them during both peak and off-peak periods. The drivers were reminded often that the experiment was designed to measure traffic conditions and not to test their abilities as drivers. They were instructed that if there was a vehicle in front of them they were to stay behind it. Otherwise, they were to drive in their usual manner. The crew in the car consisted of the two drivers and an observer. The observer directed the drivers on the routes being measured, and operated the traffic events switches. The reserve driver operated the movie camera, reset the counters, and recorded the final values of the run.

Because it would have been inefficient to travel each route separately, a set of three test run patterns was developed to cover all portions of all routes under study. An entire route was not necessarily covered within one of these patterns. The routes were divided into segments, and data for each route were obtained by combining values for the appropriate segments from the various patterns. The data on the counters were recorded on film at a distance before and after each intersection along the pattern. The camera was activated manually by means of a switch.

SITE AND STUDY DESCRIPTION

General

There are many kinds of unsignalized intersections in the Chicago metropolitan area. Intensity of control as well as complexity of street patterns increases with proximity to the center. Within the city limits of Chicago, YIELD controls are presently applied only on former Chicago Park District routes, generally on entrance ramps to Lake Shore Drive, or in park areas under special conditions. No "normal" intersections in the city are under YIELD control. These considerations led to the choice of sites in nearby suburban communities. Suburbs near the central city had sufficient volumes of traffic to make an intersection study feasible, yet did not have as many complicating factors.

Because of the nature of YIELD- and two-way STOP-controlled intersections, traffic volumes are usually relatively low on the minor street. It was difficult to find a site where the capacity of the control was being taxed, except where major-street traffic was so great that almost all vehicles on the side street were suffering undue delay.

TABLE A-1
GENERAL CHARACTERISTICS OF STUDY INTERSECTIONS

INTERSECTION	CONTROL AT INTERSECTION [1]	STREET	SPEED LIMIT (MPH)	STREET CLASSIFICATION	LEG	WIDTH (FT)	PARKING CONDITIONS
Fifth St. and Linden Ave. (site A)	None	Fifth St. (minor)	Not posted	Local access	North	28	One side
					South	28	One side
		Linden Ave. (major)	25 (posted)	Local collector	East	40	Both sides
					West	27	One side
Fifth St. and Greenleaf Ave. (site A)	YIELD	Fifth St. (minor)	Not posted	Local access	North	30	One side
					South	30	One side
		Greenleaf Ave. (major)	30	Local collector	East	40	Both sides
					West	40	Both sides
Fourth St. and Linden Ave. (site A)	4-way STOP	Fourth St.	Not posted	Local access	North	40	Both sides
					South	40	Both sides
		Linden Ave.	25	Local collector	East	40	Both sides
					West	40	Both sides
Fourth St. and Greenleaf Ave. (site A)	YIELD	Fourth St. (major)	Not posted	Local access	North	25	One side
					South	29	Both sides
		Greenleaf Ave. (minor)	Not posted	Local collector	East	38	One side
					West	38	Both sides
Kirk St. and Kostner Ave. (site B)	YIELD	Kostner Ave. (major)	Not posted	Minor arterial	North	36	Both sides
					South	36	Both sides
		Kirk St. (minor)	Not posted	Local access	East	32	Both sides
					West	32	Both sides
Oakton St. and Kostner Ave. (site B)	4-way STOP	Kostner Ave. (minor)	Not posted	Minor arterial	North	36	Both sides
					South	36	Both sides
		Oakton St. (major)	30	Major arterial	East	56	Both sides
					West	56	Both sides
Kensington Ave. and Woodlawn Ave. (site C)	YIELD	Kensington Ave. (minor)	25	Local collector	North	30	Both sides
					South	30	Both sides
		Woodlawn Ave. (major)	Not posted	Local access	East	30	Both sides
					West	30	Both sides
Ashland Ave. and Cossitt Ave. (site C)	4-way STOP	Ashland Ave.	Not posted	Local collector	North	30	One side
					South	30	One side
		Cossitt Ave.	25	Local collector	East	30	One side
					West	30	One side

[1] At start of study.

APPROXIMATE PEAK-HOUR VOL. (VEH/HR)		SAFE THEOR. APPROACH SPEED (MPH)	CONTROL AT ADJACENT INTERSECTION [1]
A.M.	P.M.		
60	60	16	YIELD
70	80	17	None
130	200	16	STOP
130	100	34	None
55	45	40	STOP
125	115	17	None
40	70	16	YIELD protected
115	80	23	YIELD protected
290	200	14	YIELD
70	110	13	None
85	150	15	None
175	140	11	None
270	185	28	STOP
105	190	22	4-way STOP
15	20	26	None
75	60	25	YIELD protected
130	185	28	STOP
110	210	28	None
45	35	24	None
35	20	24	None
110	70	16	STOP protected
130	200	30	YIELD protected
500	790	38	STOP protected
800	680	16	STOP protected
55	70	38	YIELD protected
70	80	21	YIELD protected
15	35	24	STOP protected
24	40	26	None
160	280	39	STOP protected
215	165	21	STOP protected
210	285	29	STOP protected
185	230	21	STOP protected

In these cases minor-street volume was usually small.

The five project study sites (Fig. 3) were chosen so as to provide the desired information in the three areas of research discussed in Chapter Three. Table A-1 summarizes the general characteristics of each study intersection; Table A-2 lists the films taken at each intersection. Figure A-1 shows the hourly intersection volumes at four of the study sites between 7:00 A.M. and 7:00 P.M. The morning and evening peak-hour volumes for the intersections studied are shown in Figures A-2 to A-11. Figure A-12 shows the three types of YIELD signs in place at the study intersections. Within each site, two or more field studies were carried out at two or more intersections, as described in the following.

Site A—Wilmette

The four intersections studied at site A were at the corners of the block bounded by Linden Avenue, Fourth Street, Greenleaf Avenue and Fifth Street. Plans and photographs of the intersections are shown in Figures 4 to 7. The general characteristics of each are summarized in Table A-1.

The site was initially chosen because of the relatively high volume through the uncontrolled intersection of Fifth and Linden. The volumes warranted consideration of two-way STOP control. This led to the possibility of before-and-after studies under uncontrolled, YIELD and two-way STOP conditions, with the controls to be placed on Fifth Street. It was decided that the YIELD intersections along Greenleaf at Fourth and Fifth Streets, together with the four-way STOP at Fourth and Linden, should be studied to obtain the effects on these adjacent intersections of the control changes planned at Fifth and Linden. These studies, in turn, would be usable as additional data on individual intersections.

The site area is generally residential in nature. However, a small shopping area centers on the corner of Fourth and Linden. The Chicago Transit Authority's Evanston rapid transit line also terminates at this intersection. During peak periods pedestrian traffic from the transit terminal floods the intersection intermittently. During shopping hours, and especially during evening peak periods, double parking in front of the stores adds to the congestion.

Field studies were made in peak and off-peak periods during August, September and October, 1963. The uncontrolled intersection of Fifth and Linden was studied in August. YIELD signs were installed later in the month, to control traffic on Fifth. The drivers were given one month to adjust to the change before the intersection was studied again. Upon completion of this phase of the study, the YIELD signs were replaced with two-way STOP signs. After another adjustment period of one month, the intersection was studied for the final time. Concurrently with the before-and-after studies at Fifth and Linden, similar studies were made at the adjoining intersection of Fifth and Greenleaf. This intersection remained under YIELD control.

Speeds of vehicles approaching and leaving on each leg of the intersection were determined by use of stopwatches

TABLE A-2
FILM LISTING

FILM NO.	TYPE OF CONTROL	INTERSECTION	LOCATION	DATE FILMED	TIME FILMED	PEAK OR OFF-PEAK	CONTINUOUS OR INTERMITTENT
1	YIELD	Kirk & Kostner	Skokie	6-26-63	8:30 AM-11:30 AM	Off-peak	Intermittent
2	YIELD	Kirk & Kostner	Skokie	6-26-63	11:30 AM- 3:00 PM	Off-peak	Intermittent
3	YIELD	Kirk & Kostner	Skokie	6-26-63	4:14 PM- 5:00 PM	Peak	Continuous
4	4-way STOP	Oakton & Kostner	Skokie	7-23-63	8:00 AM- 8:45 AM		Continuous
5	4-way STOP	Oakton & Kostner	Skokie	7-23-63	9:30 AM-10:15 AM		Continuous
6	4-way STOP	Oakton & Kostner	Skokie	7-23-63	4:00 PM- 4:45 PM		Continuous
7	4-way STOP	Oakton & Kostner	Skokie	7-23-63	4:45 PM- 5:30 PM		Continuous
8	YIELD	Kirk & Kostner	Skokie	7-24-63	8:00 AM-10:45 AM	Off-peak	Intermittent
9	None	5th & Linden	Wilmette	8-12-63	8:45 AM- 9:00 AM		Continuous
10	None	5th & Linden	Wilmette	8-12-63	9:15 AM-10:30 AM		Intermittent
11	None	5th & Linden	Wilmette	8-12-63	3:00 PM- 4:15 PM		Intermittent
12	None	5th & Linden	Wilmette	8-12-63	4:45 PM- 5:30 PM		Continuous
13	YIELD	5th & Greenleaf	Wilmette	8-13-63	8:30 AM- 9:15 AM	Off-peak	Continuous
14	YIELD	5th & Greenleaf	Wilmette	8-13-63	9:30 AM-11:00 AM	Off-peak	Intermittent
15	YIELD	5th & Greenleaf	Wilmette	8-13-63	3:00 PM- 4:15 PM	Off-peak	Intermittent
16	YIELD	5th & Greenleaf	Wilmette	8-13-63	4:45 PM- 5:30 PM	Peak	Continuous
17	YIELD	Woodlawn & Kensington	La Grange Pk	8-20-63	7:50 AM- 8:30 AM	Peak	Continuous
18	YIELD	Woodlawn & Kensington	La Grange Pk	8-20-63	9:00 AM-11:45 AM	Off-peak	Intermittent
19	YIELD	Woodlawn & Kensington	La Grange Pk	8-20-63	2:00 PM- 4:00 PM	Off-peak	Intermittent
20	YIELD	Woodlawn & Kensington	La Grange Pk	8-20-63	4:45 PM- 6:20 PM	Peak	Continuous
21	YIELD	4th & Greenleaf	Wilmette	8-23-63	8:30 AM- 9:15 AM	Off-peak	Continuous
22	4-way STOP	4th & Linden	Wilmette	8-23-63	4:15 PM- 5:00 PM		Continuous
23	4-way STOP	4th & Linden	Wilmette	8-23-63	5:00 PM- 5:45 PM		Continuous
24	YIELD	Kirk & Kostner	Skokie	8-28-63	7:30 AM- 8:15 AM	Peak	Continuous
25	YIELD	Kirk & Kostner	Skokie	8-28-63	8:30 AM- 9:15 AM	Off-peak	Continuous
26	4-way STOP	Ashland & Cossitt	La Grange	9-13-63	7:30 AM- 8:15 AM		Continuous
27	4-way STOP	Ashland & Cossitt	La Grange	9-13-63	9:45 AM-10:30 AM		Continuous
28	4-way STOP	Ashland & Cossitt	La Grange	9-13-63	2:30 PM- 3:15 PM		Continuous
29	4-way STOP	Ashland & Cossitt	La Grange	9-13-63	4:45 PM- 5:30 PM		Continuous
30	4-way STOP	4th & Linden	Wilmette	9-16-63	7:30 AM- 8:15 AM		Continuous
31	4-way STOP	4th & Linden	Wilmette	9-16-63	4:45 PM- 5:30 PM		Continuous
32	YIELD	4th & Greenleaf	Wilmette	9-17-63	8:30 AM- 9:15 AM	Off-peak	Continuous
33	YIELD	4th & Greenleaf	Wilmette	9-17-63	4:45 PM- 6:15 PM	Peak	Continuous
34	YIELD	5th & Greenleaf	Wilmette	9-18-63	7:45 AM- 8:30 AM	Peak	Continuous
35	YIELD	5th & Greenleaf	Wilmette	9-18-63	9:45 AM-11:15 AM	Off-peak	Intermittent
36	YIELD	5th & Greenleaf	Wilmette	9-18-63	2:45 PM- 4:30 PM	Off-peak	Intermittent
37	YIELD	5th & Greenleaf	Wilmette	9-18-63	4:45 PM- 5:30 PM	Peak	Continuous
38	YIELD	5th & Linden	Wilmette	9-19-63	7:30 AM- 8:15 AM	Peak	Continuous
39	YIELD	5th & Linden	Wilmette	9-19-63	10:15 AM-12:00 N	Off-peak	Intermittent
40	YIELD	5th & Linden	Wilmette	9-19-63	1:15 PM- 3:15 PM	Off-peak	Intermittent
41	YIELD	5th & Linden	Wilmette	9-19-63	4:45 PM- 5:30 PM	Peak	Continuous
42	Signal	Oakton & Kostner	Skokie	9-30-63	7:30 AM- 8:15 AM		Continuous
43	Signal	Oakton & Kostner	Skokie	9-30-63	4:45 PM- 5:30 PM		Continuous
44	2-way STOP	Kirk & Kostner	Skokie	10- 1-63	7:30 AM- 8:15 AM	Peak	Continuous
45	2-way STOP	Kirk & Kostner	Skokie	10- 1-63	10:00 PM-12:30 PM	Off-peak	Intermittent
46	2-way STOP	Kirk & Kostner	Skokie	10- 1-63	2:15 PM- 4:30 PM	Off-peak	Intermittent
47	2-way STOP	Kirk & Kostner	Skokie	10- 1-63	4:45 PM- 5:30 PM	Peak	Continuous
48	YIELD	4th & Greenleaf	Wilmette	10-21-63	7:30 AM- 8:15 AM	Peak	Continuous
49	YIELD	4th & Greenleaf	Wilmette	10-21-63	4:45 PM- 5:30 PM	Peak	Continuous
50	4-way STOP	4th & Linden	Wilmette	10-22-63	7:30 AM- 8:15 AM		Continuous
51	4-way STOP	4th & Linden	Wilmette	10-22-63	4:45 PM- 5:30 PM		Continuous
52	YIELD	5th & Greenleaf	Wilmette	10-23-63	7:30 AM- 8:15 AM	Peak	Continuous
53	YIELD	5th & Greenleaf	Wilmette	10-23-63	9:00 AM-12:00 N	Off-peak	Intermittent
54	YIELD	5th & Greenleaf	Wilmette	10-23-63	1:00 PM- 4:00 PM	Off-peak	Intermittent
55	YIELD	5th & Greenleaf	Wilmette	10-23-63	4:45 PM- 5:30 PM	Peak	Continuous
56	2-way STOP	5th & Linden	Wilmette	10-24-63	7:30 AM- 8:15 AM	Peak	Continuous
57	2-way STOP	5th & Linden	Wilmette	10-24-63	9:00 AM- 1:30 PM	Off-peak	Intermittent
58	2-way STOP	5th & Linden	Wilmette	10-25-63	1:30 PM- 4:30 PM	Off-peak	Intermittent
59	2-way STOP	5th & Linden	Wilmette	10-24-63	4:45 PM- 5:30 PM	Peak	Continuous
60	4-way STOP	Augusta & Lombard	Oak Park	11-12-63	7:30 AM- 8:15 AM		Continuous
61	4-way STOP	Augusta & Lombard	Oak Park	11-12-63	9:20 AM-10:00 AM		Continuous
62	4-way STOP	Augusta & East	Oak Park	11-18-63	7:30 AM- 8:15 AM		Continuous
63	4-way STOP	Augusta & East	Oak Park	11-18-63	9:30 AM-10:15 AM		Continuous
64	4-way STOP	Augusta & Woodbine	Oak Park	11-19-63	7:30 AM- 8:15 AM		Continuous
65	4-way STOP	Augusta & Woodbine	Oak Park	11-19-63	9:30 AM-10:15 AM		Continuous
66	2-way STOP	Augusta & Woodbine	Oak Park	12-10-63	7:30 AM- 8-15 AM		Continuous
67	2-way STOP	Augusta & Woodbine	Oak Park	12-10-63	9:30 AM-10:15 AM		Continuous
68	2-way STOP	Augusta & Lombard	Oak Park	12-11-63	7:30 AM- 8:15 AM		Continuous

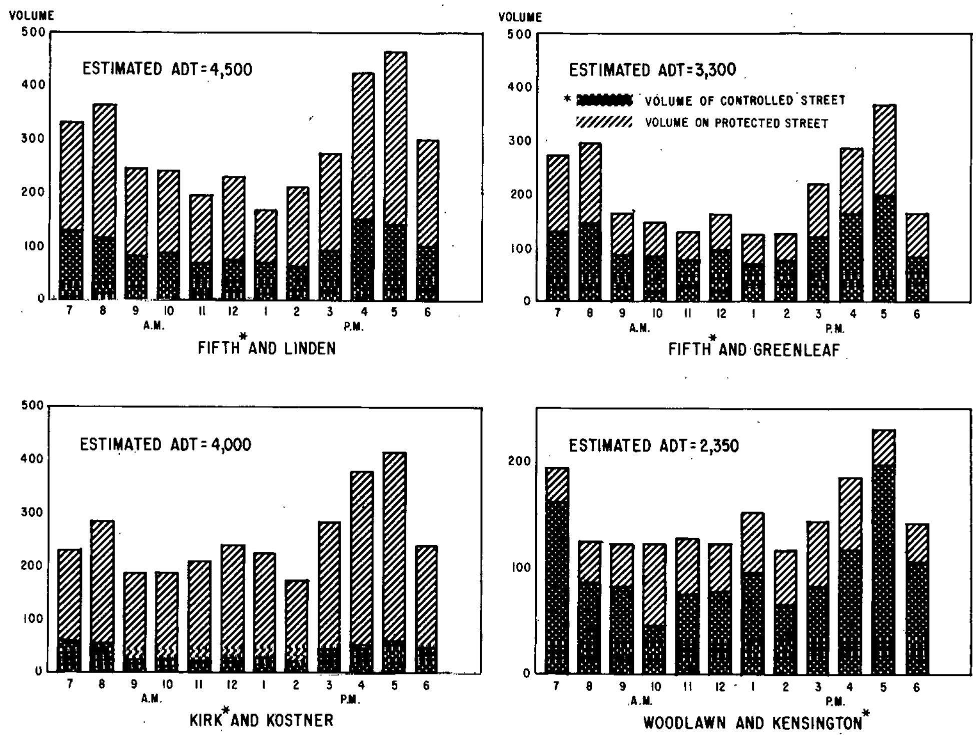


Figure A-1. Hourly intersection volumes.

and measured enoscope traps. Due to congestion on the east leg of Fifth and Linden during the evening period, most of the rush-hour data on speeds for this leg were obtained in the morning. Speed data on Fifth between Linden and Greenleaf were used for both intersections. Stopwatches and enoscopes were also used to obtain travel time. This phase of field work usually followed the speed studies and recorded the time necessary for vehicles to approach and leave the intersection over a measured distance. Films were taken during the travel-time studies. Additional films were taken to obtain information on the general operational characteristics during peak periods of the neighboring intersections along Fourth at Linden and Greenleaf.

Volume counts were taken manually by 5-min intervals during the speed and travel-time studies at Fifth and Linden and at Fifth and Greenleaf. Less detailed supplementary counts were also made at Fifth and Laurel and along Fourth at Laurel, Linden and Greenleaf.

Site B—Skokie

Two adjacent intersections were chosen for study in the Village of Skokie. During the study, the controls were changed at each of the intersections. The plan and photographs of the site are shown in Figures 8 and 9. The general characteristics of the intersections are summarized in Table A-1.

The intersection of Oakton Street and Kostner Avenue had been scheduled for an upgrading of control from a four-way STOP to a vehicle-actuated signal. This provided an excellent opportunity to conduct a before-and-after study; the results of the studies at this intersection are not included in this report, but will be presented at a later date. Kirk Street and Kostner Avenue, immediately to the south, was under YIELD control, protecting Kostner. Arrangements were made to study the operation under the existing conditions and then under two-way STOP control.

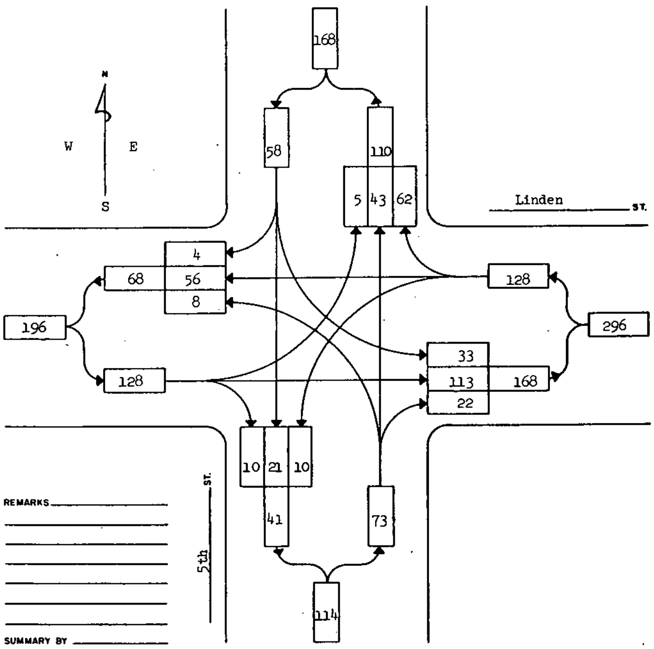
Development along Kostner is generally residential, although the street serves as a minor arterial route. Oakton serves as a major arterial for Skokie and many other north suburban communities. The street is also used as a bus route. Development along the street is generally commercial and primarily retail. Kirk is a local access street with residential character.

Field studies were made in peak and off-peak periods during the five-month period from June through October. Kirk was initially controlled by YIELD signs protecting Kostner and then changed to two-way STOP control in connection with a before-and-after study. A portion of the field studies was conducted jointly with G. Radelat *, during which the vehicles on Kirk were traced through the intersection by means of a 20-pen graphic recorder. The crew consisted of five observers actuating buttons and tending the recorder, which was used to obtain speed profiles, travel time, and headway characteristics of minor-street vehicles. These data supplemented the field studies for the project. Speeds for Kostner were obtained with stopwatches and enoscopes. Films recorded peak and off-peak characteristics. The intersection was changed to two-way STOP control in late August. A period of a month was allowed for drivers to adjust to the new situation. In the studies after the change in control, the 20-pen graphic recorder was replaced by manual methods and camera studies.

* Radelat, *Ibid.*

VEHICLE VOLUME COUNT
GRAPHIC SUMMARY SHEET

DATE Sept. 19, '63 DAY Thursday WEATHER Fair TIME 7:45 A.M. TO 8:45 A.M.
LOCATION: DISTRICT ____ COUNTY ____ RURAL ☐ CITY Wilmette
INTERSECTION OF 5th AND Linden



REMARKS ____

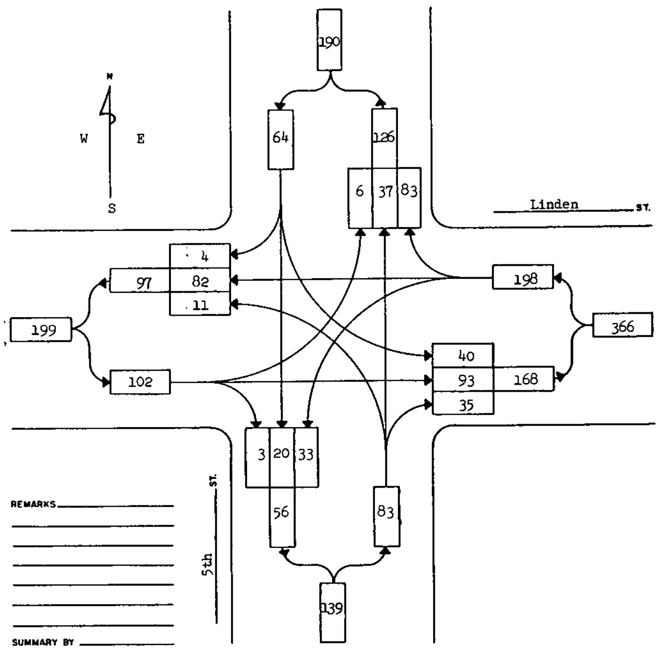
SUMMARY BY ____

INTERSECTION LEG			INBOUND	OUTBOUND	TOTAL
N LEG OF	5th	ST.	58	110	168
S LEG OF	5th	ST.	73	41	114
E LEG OF	Linden	ST.	128	168	296
W LEG OF	Linden	ST.	128	68	196
LEG OF		ST.			
LEG OF		ST.			
TOTAL			387	387	774

Figure A-2.

VEHICLE VOLUME COUNT
GRAPHIC SUMMARY SHEET

DATE Sept. 19, '63 DAY Thursday WEATHER Fair TIME 4:30 P.M. TO 5:30 P.M.
LOCATION: DISTRICT ____ COUNTY ____ RURAL ☐ CITY Wilmette
INTERSECTION OF 5th AND Linden



REMARKS ____

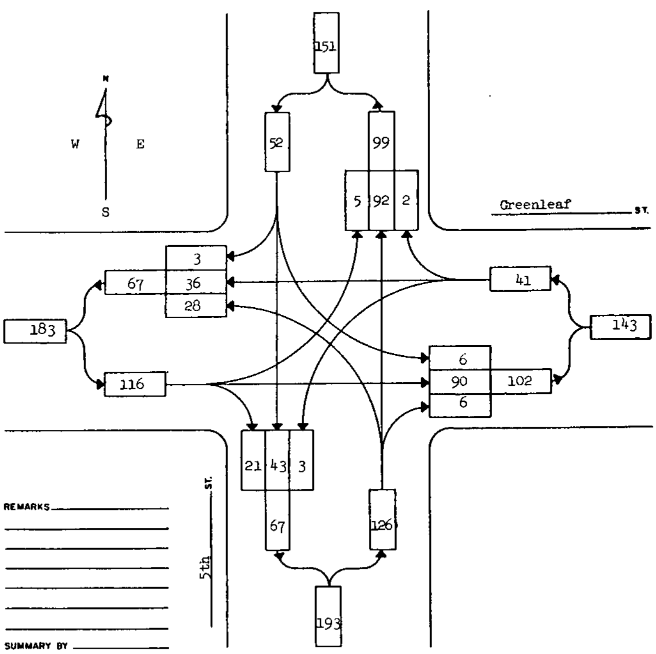
SUMMARY BY ____

INTERSECTION LEG			INBOUND	OUTBOUND	TOTAL
N LEG OF	5th	ST.	64	126	190
S LEG OF	5th	ST.	83	56	139
E LEG OF	Linden	ST.	198	168	366
W LEG OF	Linden	ST.	102	97	199
LEG OF		ST.			
LEG OF		ST.			
TOTAL			447	447	894

Figure A-3.

VEHICLE VOLUME COUNT
GRAPHIC SUMMARY SHEET

DATE Sept. 17, '63 DAY Tuesday WEATHER Fair TIME 7:25 A.M. TO 8:25 A.M.
LOCATION: DISTRICT ____ COUNTY ____ RURAL ☐ CITY Wilmette
INTERSECTION OF 5th AND Greenleaf



REMARKS ____

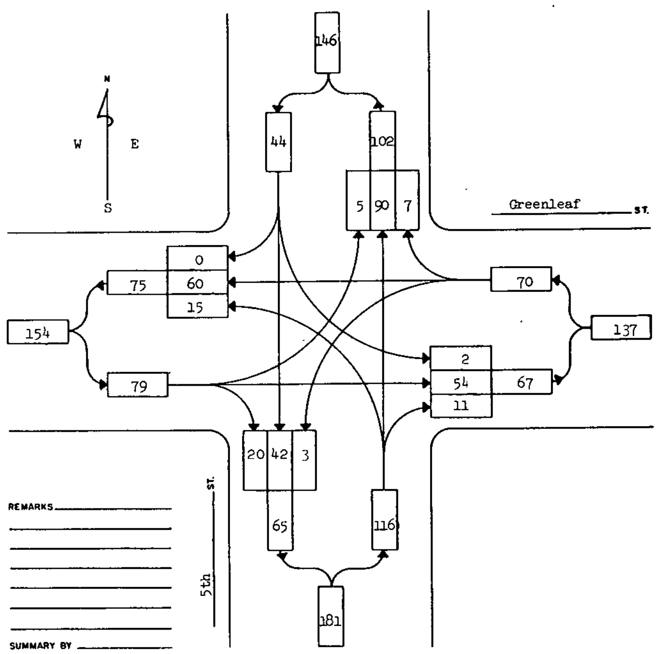
SUMMARY BY ____

INTERSECTION LEG			INBOUND	OUTBOUND	TOTAL
N LEG OF	5th	ST.	52	99	151
S LEG OF	5th	ST.	126	67	193
E LEG OF	Greenleaf	ST.	41	102	143
W LEG OF	Greenleaf	ST.	116	67	183
LEG OF		ST.			
LEG OF		ST.			
TOTAL			335	335	670

Figure A-4.

VEHICLE VOLUME COUNT
GRAPHIC SUMMARY SHEET

DATE Sept. 18, '63 DAY Tuesday WEATHER Fair TIME 4:30 P.M. TO 5:30 P.M.
LOCATION: DISTRICT ____ COUNTY ____ RURAL ☐ CITY Wilmette
INTERSECTION OF 5th AND Greenleaf



REMARKS ____

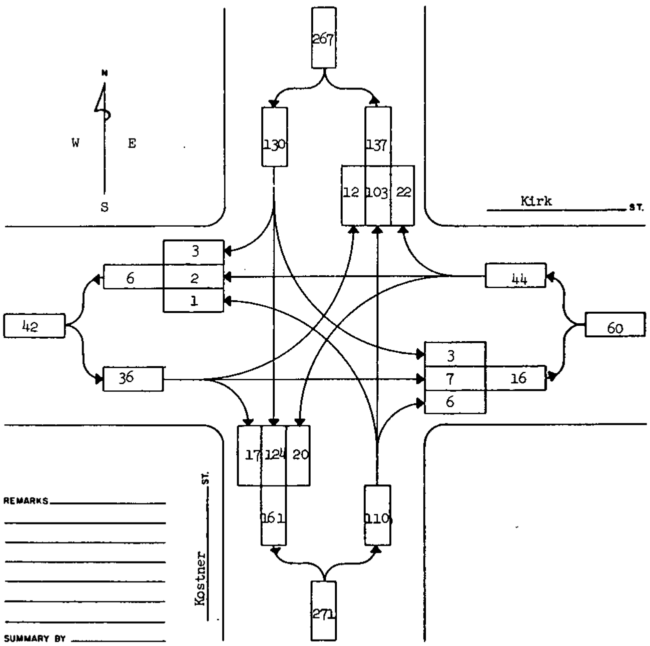
SUMMARY BY ____

INTERSECTION LEG			INBOUND	OUTBOUND	TOTAL
N LEG OF	5th	ST.	44	102	146
S LEG OF	5th	ST.	176	65	181
E LEG OF	Greenleaf	ST.	70	67	137
W LEG OF	Greenleaf	ST.	79	75	154
LEG OF		ST.			
LEG OF		ST.			
TOTAL			309	309	618

Figure A-5.

VEHICLE VOLUME COUNT
GRAPHIC SUMMARY SHEET

DATE Sept. 30, '63 DAY Monday WEATHER Fair TIME 7:45 A.M. TO 8:45 A.M.
LOCATION: DISTRICT ____ COUNTY ____ RURAL ☐ CITY Skokie
INTERSECTION OF Kirk AND Kostner

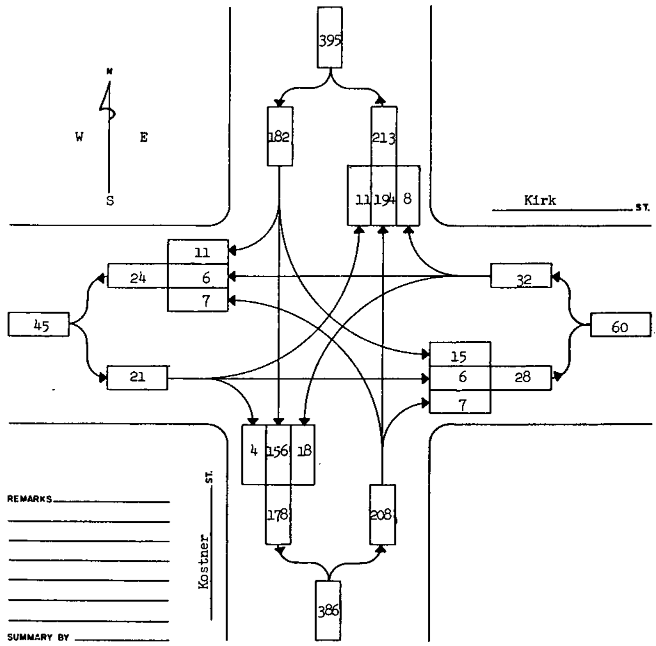


INTERSECTION LEG		INBOUND	OUTBOUND	TOTAL
N LEG OF Kostner	ST.	130	137	267
S LEG OF Kostner	ST.	110	161	271
E LEG OF Kirk	ST.	44	16	60
W LEG OF Kirk	ST.	36	6	42
LEG OF	ST.			
LEG OF	ST.			
TOTAL		320	320	640

Figure A-6.

VEHICLE VOLUME COUNT
GRAPHIC SUMMARY SHEET

DATE Sept. 30, '63 DAY Monday WEATHER Fair TIME 4:30 P.M. TO 5:30 P.M.
LOCATION: DISTRICT ____ COUNTY ____ RURAL ☐ CITY Skokie
INTERSECTION OF Kirk AND Kostner

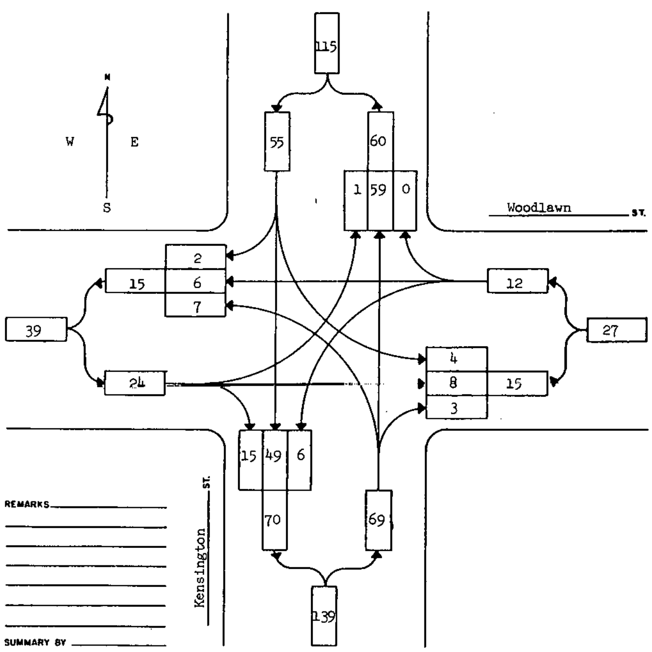


INTERSECTION LEG		INBOUND	OUTBOUND	TOTAL
N LEG OF Kostner	ST.	182	213	395
S LEG OF Kostner	ST.	208	178	386
E LEG OF Kirk	ST.	32	28	60
W LEG OF Kirk	ST.	21	24	45
LEG OF	ST.			
LEG OF	ST.			
TOTAL		443	443	886

Figure A-7.

VEHICLE VOLUME COUNT
GRAPHIC SUMMARY SHEET

DATE Aug. 19, '63 DAY Monday WEATHER Fair TIME 7:30 A.M. TO 8:30 A.M.
LOCATION: DISTRICT ____ COUNTY ____ RURAL ☐ CITY La Grange
INTERSECTION OF Kensington AND Woodlawn

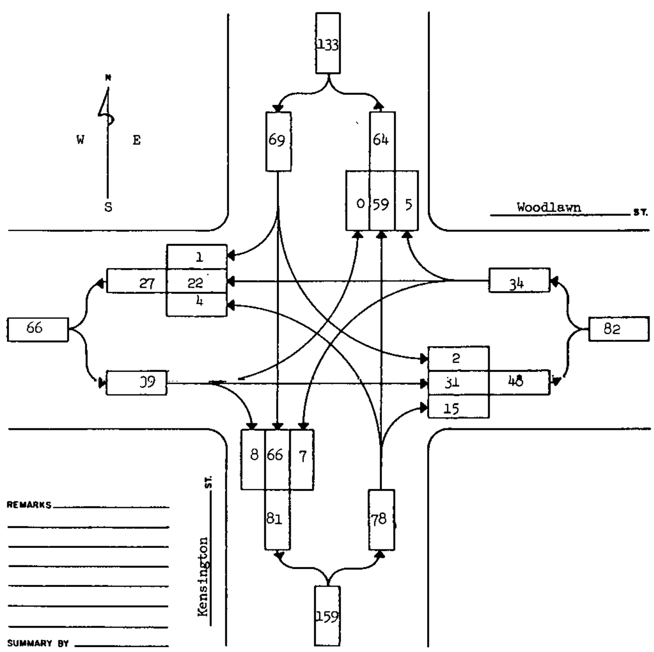


INTERSECTION LEG		INBOUND	OUTBOUND	TOTAL
N LEG OF Kensington	ST.	55	60	115
S LEG OF Kensington	ST.	69	70	139
E LEG OF Woodlawn	ST.	12	15	27
W LEG OF Woodlawn	ST.	24	15	39
LEG OF	ST.			
LEG OF	ST.			
TOTAL		160	160	320

Figure A-8.

VEHICLE VOLUME COUNT
GRAPHIC SUMMARY SHEET

DATE Aug. 19, '63 DAY Monday WEATHER Fair TIME 4:30 P.M. TO 5:30 P.M.
LOCATION: DISTRICT ____ COUNTY ____ RURAL ☐ CITY La Grange
INTERSECTION OF Kensington AND Woodlawn

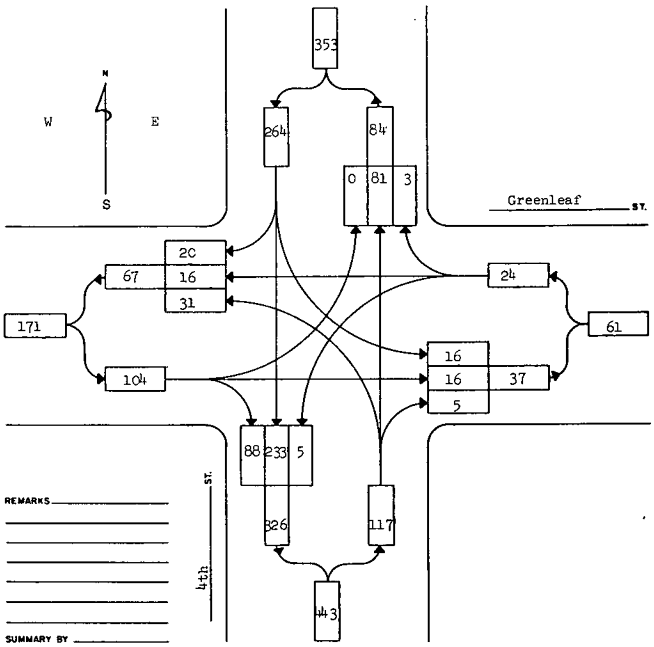


INTERSECTION LEG		INBOUND	OUTBOUND	TOTAL
N LEG OF Kensington	ST.	69	64	133
S LEG OF Kensington	ST.	78	81	159
E LEG OF Woodlawn	ST.	34	48	82
W LEG OF Woodlawn	ST.	39	27	66
LEG OF	ST.			
LEG OF	ST.			
TOTAL		220	220	440

Figure A-9.

VEHICLE VOLUME COUNT
GRAPHIC SUMMARY SHEET

DATE Sept. 9 '63 DAY Monday WEATHER Fair TIME 7:25 A.M. TO 8:25 A.M.
LOCATION: DISTRICT ____ COUNTY ____ RURAL ☐ CITY Wilmette
INTERSECTION OF 4th AND Greenleaf

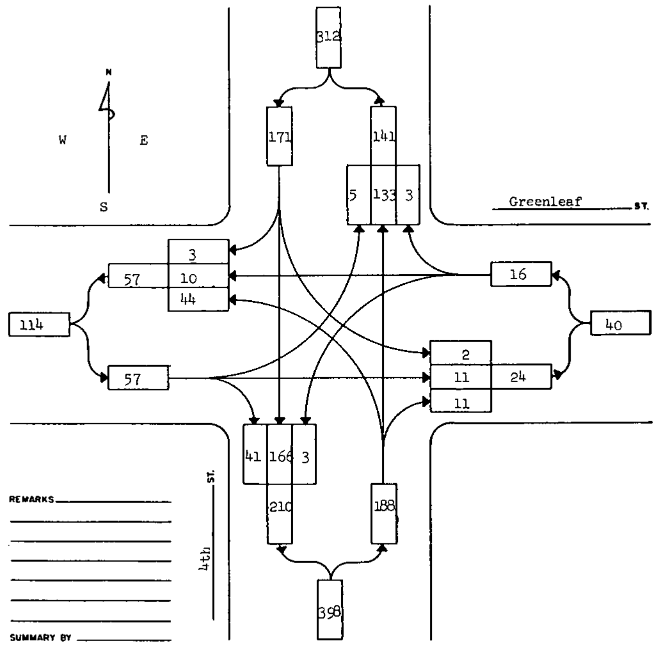


INTERSECTION LEG	INBOUND	OUTBOUND	TOTAL
N LEG OF 4th ST.	269	84	353
S LEG OF 4th ST.	117	326	443
E LEG OF Greenleaf ST.	24	37	61
W LEG OF Greenleaf ST.	104	67	171
LEG OF ST.			
LEG OF ST.			
TOTAL	514	514	1028

Figure A-10.

VEHICLE VOLUME COUNT
GRAPHIC SUMMARY SHEET

DATE Sept. 9, '63 DAY Monday WEATHER Fair TIME 4:30 P.M. TO 5:30 P.M.
LOCATION: DISTRICT ____ COUNTY ____ RURAL ☐ CITY Wilmette
INTERSECTION OF 4th AND Greenleaf



INTERSECTION LEG	INBOUND	OUTBOUND	TOTAL
N LEG OF 4th ST.	171	141	312
S LEG OF 4th ST.	188	210	398
E LEG OF Greenleaf ST.	16	24	40
W LEG OF Greenleaf ST.	57	57	114
LEG OF ST.			
LEG OF ST.			
TOTAL	432	432	864

Figure A-11.

Site C—LaGrange and LaGrange Park

Two separate intersections in the LaGrange-LaGrange Park area provided suitable study conditions. The intersection of Kensington Avenue and Woodlawn Avenue in LaGrange Park was YIELD controlled and carried a relatively high volume of traffic. The four-way STOP intersection of Cossitt and Ashland in LaGrange was also studied. However, the analysis will be conducted during a later stage of the project. The plans and photographs of the intersections are shown in Figures 10 to 12, and the general characteristics of each are summarized in Table A-1.

The intersection of Kensington and Woodlawn is located in a residential area with neighboring shopping districts and a school. A small business area one block to the east on Woodlawn contains several stores and the LaGrange Park city hall, including police and fire departments. The major shopping areas are a shopping plaza three blocks to the east, and the downtown area of LaGrange to the south. Many residents commute to Chicago via the Burlington Railroad. During peak periods the LaGrange depot is the origin or destination of many vehicles using Kensington. At a grade school one block north of Woodlawn on Kensington, patrol boys assist children in crossing the street. However, the studies were completed before the school term began, hence children and patrol boys were not a factor. Kensington is a local collector and Woodlawn is a local access street. The Village of LaGrange Park has designated Woodlawn as a police and fire lane. Consequently, the major traffic flow on Kensington was required to yield. No control change was carried out at this site. The intersection data were combined with data from other study intersections with the same type of control.

Speed, travel-time, photographic and volume studies were performed during August in peak and off-peak periods. Vehicle speeds for each leg of Kensington were studied by means of stopwatches and enoscopes. Woodlawn, due to the relatively short block lengths, was studied as a single unit by a continuous set of enoscope traps to obtain the speed profile through the intersection. A travel-time study was made for vehicles on Kensington, while the same data for Woodlawn were obtained by adding the times recorded on the continuous speed profile. Even though these results showed only times for through movements, they were judged to be adequate because the various turning movements were a small percentage of the total. Filming was done during the travel-time studies for Kensington. Manual volume counts were taken throughout the study.

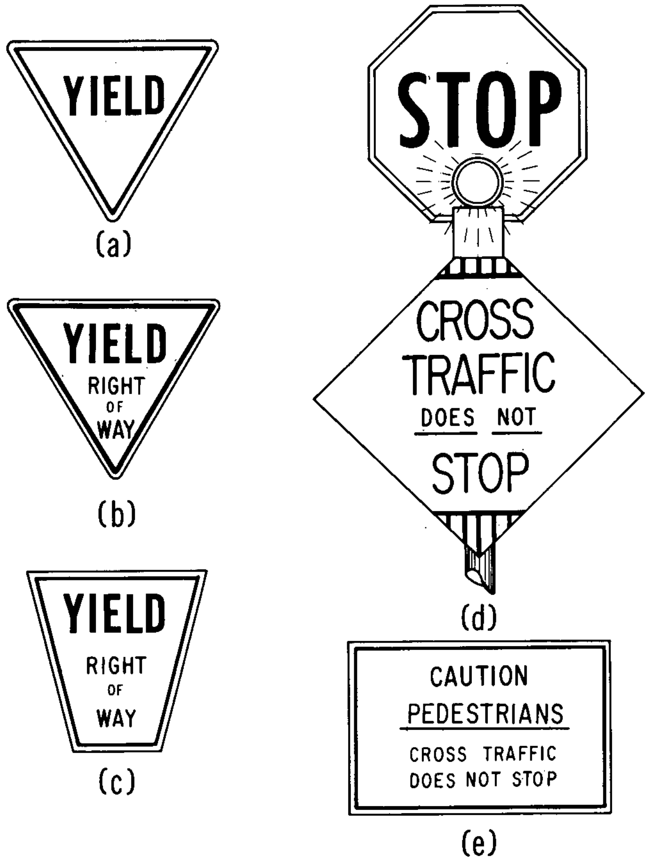


Figure A-12. YIELD *and supplementary signs used during study.*

Site D—Oak Park

More than 400 miles of streets in the Chicago metropolitan area were surveyed to find one site with all the characteristics desired for a study of the effects of a set of controls on operation within a travel corridor. The site in the Village of Oak Park is shown in plan view and with photographs in Figures 13 and 14. The corridor is approximately 1½ miles long and about ⅓ mile wide. The major alternative east-west routes through the area are Division and Augusta Streets. Drivers form other alternative routes by transferring between Division and Augusta within the study area, via one of the cross streets. The study was carried out during morning hours only, avoiding the darkness which occurred during the evening peak at the time of the year that the field work was conducted.

Division carried a total of about 700 vehicles in both directions in the peak hour, whereas Augusta served about 550. Within the Village of Oak Park, Division and Augusta have approximately the same width and character, although Division is included in a preferential street system while Augusta is not. Signs posted along Augusta at a few places state that it is not a through street. This precaution was apparently deemed desirable because Augusta Street in Oak Park is an extension of Augusta Boulevard in Chicago, which is a through street. However, drivers tend to disregard the warning signs, as shown by the results of the survey.

The development along the alternative routes is almost entirely residential. There is a school on each street with guards at heavily used crossings. Traffic on both Division and Augusta is composed predominantly of passenger vehicles. The major physical differences between the two streets are (a) the presence of three four-way STOPS on Augusta, (b) the rough pavement on Division, and (c) an annoying traffic signal at the offset intersection of Division and Ridgeland.

To the east, within the Chicago City limits, Augusta becomes an important boulevard route which terminates at the intersection of a major northwest radial route. Division Street is also an important through route serving traffic with destinations in, and to the north and west of, the central city.

Before-and-after studies were conducted in November and December during both morning peak and off-peak periods. The evening peak period was omitted due to early darkness at that time of year. The intersections along Augusta at Woodbine, East, and Lombard were first studied under four-way STOP conditions. Speeds were taken for through vehicles on Augusta leaving either side of each study intersection. One trap was used to obtain the average maximum speed attained during the first block beyond the intersection. Stopwatches and enoscopes were used to measure speeds of individual cars. Films were taken of the operational characteristics at the four-way STOP intersections. These were run continu-

ously because the level of traffic on Augusta was fairly high even during the off-peak period. Volume counts of peak and off-peak periods were taken at the intersections of Woodbine, East and Lombard along Augusta and Division.

A questionnaire was handed out during morning peak and off-peak periods to eastbound vehicles on Division and Augusta at their intersections with Austin. The crew at each intersection consisted of several men distributing questionnaires and one observer counting eastbound vehicles during the period of distribution. Only vehicles stopped by the traffic signal were questioned.

After the Village Board passed a temporary ordinance, the four-way STOP controls were removed from Augusta at Woodbine, East, and Lombard and replaced by two-way STOP controls protecting Augusta. As an extra precaution for the safety of the pedestrians and motorists, special signs were erected to warn of the change. These signs, also shown in Figure A-12, were erected on the minor-street approaches at each side of the three intersections where the four-way STOP control was replaced by two-way STOP signs.

Due to the short period allowed for temporary change in controls, the adjustment period for drivers was only three weeks. Afterwards, the speeds of vehicles on Augusta leaving these intersections were once more obtained by stopwatches and enoscopes. Manual volume counts were made along Division and Augusta at the same locations used during the before study. Films were not taken after the change in control due to cold weather conditions.

During the after studies, another questionnaire was handed out at the same two locations and using the same methods as before.

The instrumented vehicle was used to gather data on test runs throughout the before-and-after study. Toward the end of the study period, operation was hampered somewhat by inclement weather, but the streets were generally free of snow and ice during the runs.

Site E—Skokie

A secondary system study was carried out in the Village of Skokie. Data were obtained by the instrumented vehicle and by questionnaires. A plan of the site is shown in Figure 15. The primary routes for westbound traffic approaching the interchange of Dempster Street at Edens Expressway were studied. These included routes formed by Dempster, Church, Niles Center, Gross Point, Laramie and Lockwood.

The study was conducted (a) to provide supplemental information which could be analyzed in a later stage of the project; and (b) to have data available for analysis along with the Oak Park before study, should the late fall weather make completion of the after study impossible. Conditions did permit completion of the after study in Oak Park; therefore, data from the Skokie system study are not included in this report.

APPENDIX B

METHODS OF ANALYSIS

The methods used in analyzing the data collected and discussed in the main body of this report are discussed here. Detailed discussion of special techniques is included, but other methods are discussed only briefly. The methods used to collect the data are described briefly in the main text, and in detail in Appendix A.

MANUALLY RECORDED DATA

Speed Profiles

Speed profiles were collected on the legs of a number of the study intersections. Speeds for each "trap" were averaged. The average speed was plotted and a smooth curve was fitted to the points by eye. For the intersections where control changes were carried out as a part of the study, the profiles for each control condition were plotted together and compared. Statistical tests of the speeds in each trap were conducted to determine if there was a significant change in speed after a change in control. The standard test was conducted to determine the significance of difference of two sample means using Student's t-distribution. The analysis was conducted to determine the effect on speeds of YIELD and STOP control as well as of sight distance. The profiles also could be used to study the interaction between adjacent intersections.

Travel Time

The data on travel times were first correlated with the 5-min intersection volumes taken concurrently. Travel times taken at the same level of major-street and minor-street volumes were grouped together. Sample sizes were so small with this grouping, however, that the average travel time for each 1-hr period was determined. The total hourly major- and minor-street volumes were also determined. The travel times for minor-street vehicles proceeding straight through were plotted against the corresponding major-street volumes to determine the effect

of major-street volume on minor-street delay. Where data were collected for YIELD and STOP control at the same intersection, the two curves were plotted for comparison. To estimate actual delay to the vehicle, the unrestricted travel time for such vehicles was computed for each intersection. The unrestricted travel time was based on a constant speed of 25 mph (the speed limit on the streets studied) across the travel-time trap. The difference between the actual travel times and this value is the delay based on one set of assumptions.

Volumes

Manual volume counts were made for several purposes during the course of the study. Peak-hour turning-movement counts were taken at each intersection in order to estimate the level of operation. Counts were also made in connection with speed profile and travel-time studies. These counts were made by successive 5-min periods, and later correlated with the data on travel time as previously discussed. An attempt was made, concurrently with the volume counts, to record the number of times there were potential conflicts between vehicles on the major and minor streets. The object was to measure how much vehicles on one street were affected by vehicles on the other. However, it was found difficult to define this accurately in the field and still count traffic. Manual turning-movement counts were also made in connection with the route study. Volumes were measured at six locations within the study area before and after the change in controls, but the change in weather and holiday conditions rendered those data useless. Manual counts were also made at the two stations where driver questionnaires were distributed. This permitted the size of the sample to be computed.

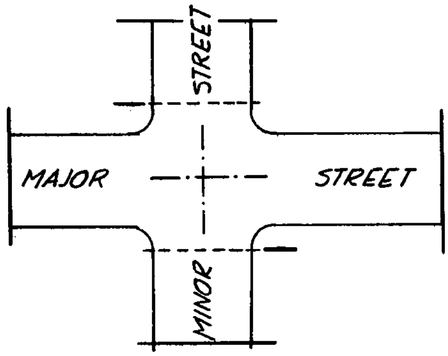
PHOTOGRAPHIC DATA

Recording

Films were made at each study intersection with a time-lapse camera operating at 100 frames per minute. This gave an accuracy of one frame interval equal to 0.6 sec. The films were made both by running the entire 100-ft roll without stopping, and by running only when vehicles were approaching on the minor street. The first is referred to as "continuous" and the second as "intermittent" filming.

The best method of analyzing the film data on the study intersections was found to be the use of automatic data processing equipment. Programs for the IBM 1401 computer were written in Fortran language for (a) calculation of gap and lag acceptance characteristics, and (b) average speeds and volumes for three time intervals, and stopped-time delay. A third program written in Autocoder language was developed to determine headways of arrival and departure. The flow diagrams for these programs are shown in Figures B-1 to B-3.

A method was devised of obtaining information from the film in the form of frame numbers which could be punched on data cards and put directly in the computer for processing. Times of occurrence of several items were defined for recording. Those referenced to points on the roadway included (see sketch):



1. Time of crossing the arrival and departure lines on each leg (solid lines). These were 50 to 100 ft from the intersection proper.
2. Time of crossing the midpoint line by the major-street vehicle.
3. Time of passing the control device (dashed line) on the minor street. Two other points, referenced purely as points in time, were used in connection with the minor-street vehicle. They are (a) the time at which the vehicle stopped, and (b) the time at which the vehicle started again.

The films were analyzed using a modified Kodak Analyst projector, which has been described in detail elsewhere (6.13). The observer could run the film forward or backward one frame at a time. Each frame was counted on a counter mounted on the projector. The method described almost completely eliminated the need to reverse the film. As each frame showed one of the vehicles at a point to be recorded, the observer entered the frame number in the appropriate place on the analysis form. Simplification of the data recording process reduced the analysis time to about 50 percent, it is estimated, of the time that would have been required using more conventional techniques.

Processing

After recording on the analysis forms, the data were punched into IBM cards, each card representing one vehicle and containing all information concerning that vehicle. Major-street and minor-street cards were kept separate and in the same order as recorded from the films. The data for each film, therefore, were fed to the computer in two decks—a minor-street deck and a major-street deck—for the following operations:

1. For the gap and lag acceptance program (Fig. B-1), the computer read the first minor-street card, checked whether or not this vehicle was a "tailgater" that should be eliminated from the analysis (see text), and then read the first major-street card. It then compared the film frame number of the minor-street vehicle when it was opposite the control sign with the frame number of the major-street vehicle when it was at the center of the intersection. This was done to determine whether or not the

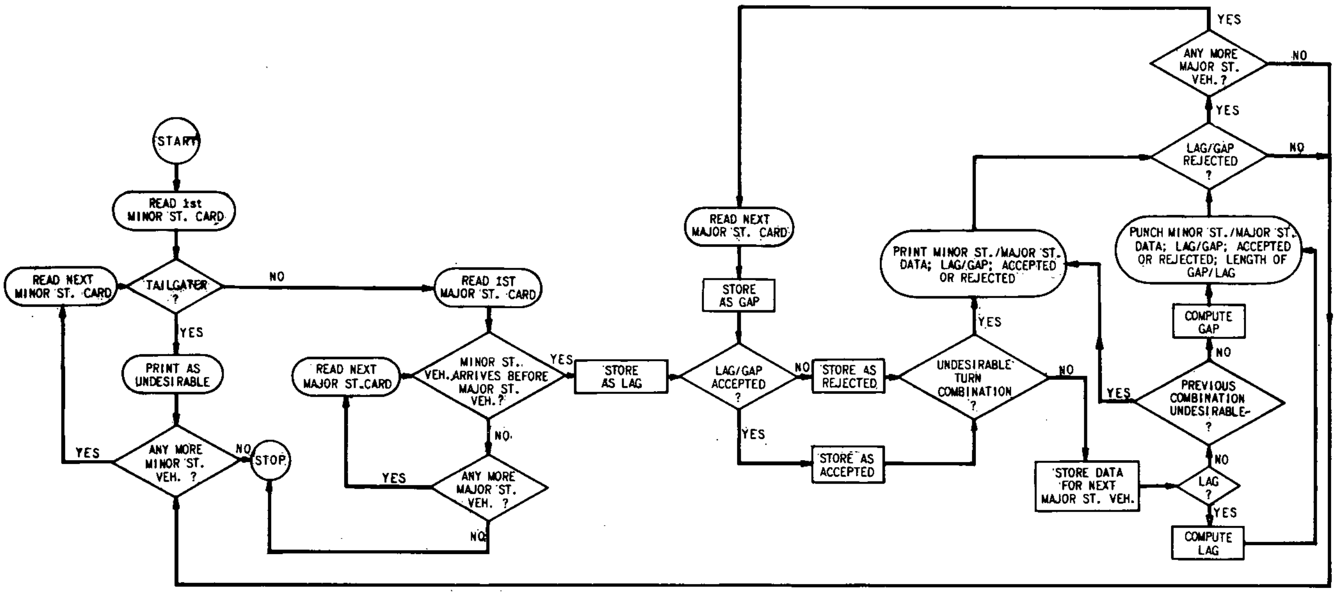
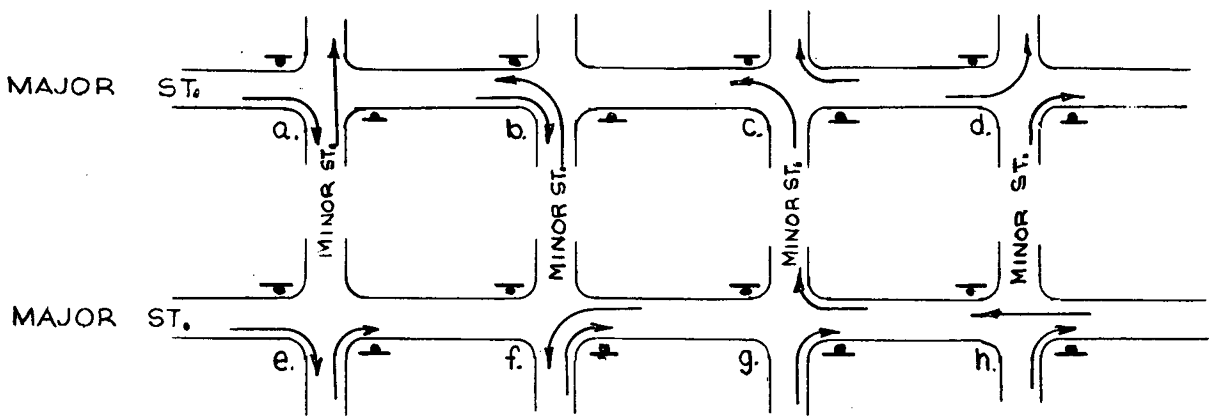


Figure B-1. Flow chart of gap and lag acceptance program.

major-street vehicle formed a lag with the minor-street vehicle. If it did not, the computer went through the major-street deck until it found the appropriate vehicle which did form a lag. It then determined if the lag was accepted or rejected by comparing the frame number of the minor-street vehicle as it started across the intersection with the frame number of the major-street vehicle when it reached the center of the intersection. The next step was to sort out this lag and determine if it was formed by one of the following turn combinations (see sketch):



a. Minor-street vehicle proceeding straight through an intersection with major-street vehicle approaching from the left and turning right.

b. Minor-street vehicle turning left with major-street vehicle approaching from the left and turning right.

c. Minor-street vehicle turning left with major-street vehicle approaching from the right and turning right.

d. Minor-street vehicle turning right with major-street vehicle approaching from the left and turning left.

e. Minor-street vehicle turning right with major-street vehicle approaching from the left and turning right.

f. Minor-street vehicle turning right with major-street vehicle approaching from the right and turning left.

g. Minor-street vehicle turning right with major-street vehicle approaching from the right and turning right.

h. Minor-street vehicle turning right with major-street vehicle approaching from the right and proceeding straight through intersection.

These were chosen so as to eliminate cases where no interference occurred between major- and minor-street vehicles. Failure to signal on the part of one of the vehicles could cause enough doubt on the driver's part so that normal operating conditions would not be represented.

If the lag was not formed by one of these combinations, it was calculated and punched on an output card by the computer. If the lag was rejected, the computer read the next major-street card, called this formation a gap, and

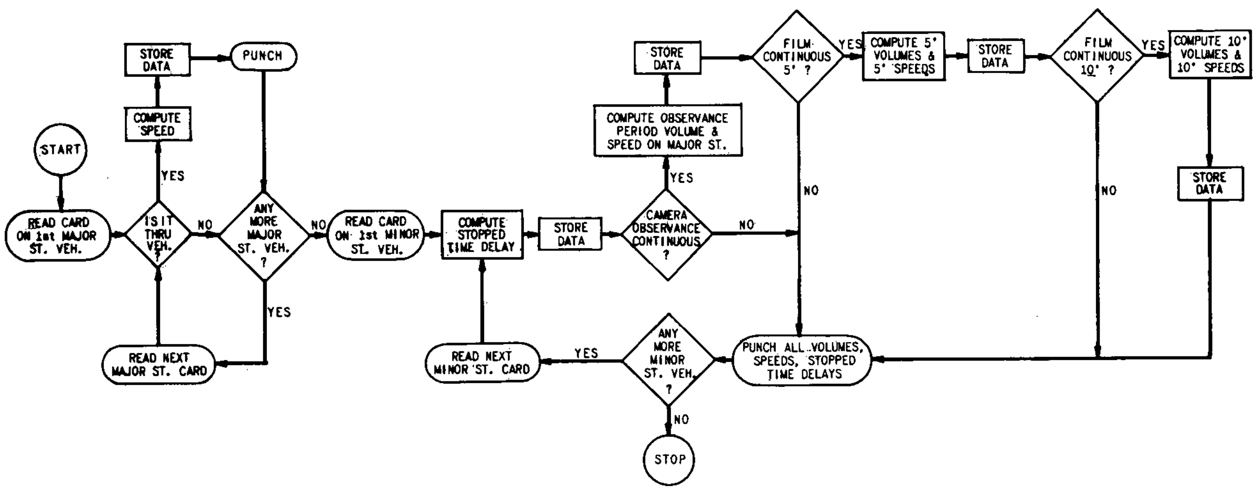


Figure B-2. Flow chart of speed, volume and delay program.

proceeded in a similar manner. The computer continued reading major-street cards and calculating rejected gaps until it found a gap (or lag if it was the first one) that was accepted by the minor-street vehicle, at which time it read the next minor-street card and repeated the entire cycle.

If the lag formed was one of the previously listed turn combinations, it was printed out separately by the computer, complete with all pertinent data, for possible analysis in the future. If this lag (or gap) was rejected, another gap involving the minor-street vehicle was formed by the next major-street vehicle. Even if these vehicles did not form one of the turn combinations listed, this gap also was removed from the analysis. (A gap was considered to be the spacing of two successive major-street vehicles as they crossed the center of an intersection. If the first vehicle forms a turn combination that was eliminated, even though the following vehicle did not, this gap was also eliminated because the behavior of this first vehicle could have affected the minor-street driver's decision to accept or reject).

The output of this program was punched directly onto cards by the computer. It consisted of all input data concerning both vehicles (minor street and major street), whether these vehicles were involved in a gap or lag, whether the minor-street vehicle accepted or rejected, and the length of the gap or lag. These cards were then put into order of increasing gap or lag length; sorted by accepted lag, rejected lag, accepted gap, rejected gap; and printed out. It should be noted that each film was processed separately.

2. For the average speed, volume and stopped-time delay program (Fig. B-2), the computer read each major-street card, computed the speed of the vehicle through the intersection, and punched the speed and input data on output cards. It then read a minor-street card, computed the time this vehicle was delayed at the control, and counted and averaged the intersection speeds of all major-street vehicles passing through the intersection for the observation period described in the text. The program was written to perform the same operation for a 5-min period (2½ min before and after the minor-street vehicle reached the control sign) and also for a 10-min period (defined similarly). Finally, it punched the stopped-time delay, volumes, and averaged speeds for all three periods on output cards. The program did not compute data for the three periods for films which were taken intermittently.

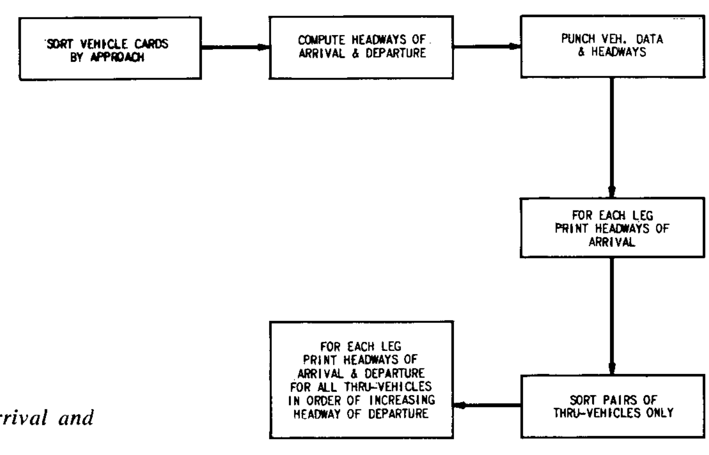


Figure B-3. Block diagram of headways of arrival and departure programs.

These cards were then put into order of increasing magnitude, sorted, and printed for observance interval volume, observance interval average speed, 5-min volume, 5-min average speed, 10-min volume, and 10-min average speed.

3. The calculation of headways of arrival and departure was originally planned to be carried out on standard equipment (as shown in the flow chart) due to its simplicity. With the large volume of cards involved in the calculation, however, it proved to be better to use the computer, programmed to the same flow chart (Fig. B-3).

Statistical analyses were performed on the data to test a number of relationships. For gap and lag acceptance, statistical tests were run to determine the significance of the differences found between STOP and YIELD control. The test determined the significance of differences between two population percentages. It assumed the values to vary according to the binomial distribution. Headway distributions were tested in a similar manner. Results concerning stopped-time delay were tested by the same method employed for the speed profiles, as previously discussed.

Additional Film Analyses

As work on the analysis of the individual intersection data progressed, a study was also made of driver obedience at each of the study intersections. The films of the intersections provided a good source of data. Each of the films of intersections under two-way STOP control was reviewed to determine (a) the percentage of minor-street drivers required to stop by cross traffic, (b) the percentage of minor-street drivers coming to a complete stop with no conflict on the major street, (c) those drivers which came to a "rolling" stop (between 0 and 5 mph), and (d) those who did not slow below 5 mph. The accuracy of this analysis depended heavily on the judgment of the observer. It is reasoned, however, that the judgment was consistent thereby allowing a fairly accurate comparison of operation of different intersections and controls. A similar analysis was conducted for films of YIELD-controlled intersections. An estimate was made of the number of drivers who passed the YIELD sign at a speed in excess of 20 mph. This was used as a criterion for determining the level of disobedience of the YIELD sign.

ROUTE STUDY DATA

As described in the main text, the drivometer registered data on a series of counters whose readings were filmed at specified points along the routes being measured. The data were read directly off the films and punched onto IBM cards. Seven major items were used for the analysis, as given in Table 5. The average of these items was determined for each route under study. The differences in the average peak-period values between the before and the after studies were tested statistically. Student's t-distribution was used to test the significance of difference between two population means. The results of these tests are summarized in Table 5.

Returned questionnaires were separated by station and period of day during which they were handed out. A tabulation was made of the number using each path through the system for the before study. The questionnaires returned from the after study were tabulated to show the driver's present route, whether he had altered his route since the control change and, if so, what his old route had been.

The limited sample available for all but the few major routes made it necessary to combine many of the questionnaire returns in order to obtain adequate samples. For this purpose, the corridor was divided into four zones in coding and analyzing the questionnaires. The larger samples gave fairly reasonable statistical results.

The four zones, which transverse the study corridor, lay between Harlem and Woodbine Avenues, Woodbine and East Avenues, East and Lombard Avenues, and Lombard and Austin Avenues (see Fig. 13).

For each of these major zones, the questionnaires were arranged into the following groups:

(a) Non-through eastbound traffic moving along Division Street, as well as similar traffic along Augusta Street, which passed the Austin Avenue stations.

(b) Eastbound traffic passing the Augusta Street station which used Division Street for some part of its route through the study corridor.

(c) Eastbound traffic passing both stations which originated within those parts of the four zones bounded by Division and Augusta Streets and Harlem and Austin Avenues.

The data were grouped and plotted on a series of graphs for analysis. It soon became evident, however, that the results obtained from this method of grouping were misleading.

Therefore, a further refinement was made in the grouping. The returns were expanded to comparable sample size, and through trips were included. In addition, the two inner zones were divided into two subzones. The data resulting from this regrouping were plotted in Figure 72.

The resulting proportions taking various routes before and after the control change were tested statistically to determine if proportions differed significantly. The test used was that for evaluating the significance of difference between two population percentages. It assumes that the population sampled follows a binomial distribution. The results of the review of the tabulations and tests are reported in Chapter Four.

Information on the origin and destination of the drivers replying was also tabulated from the questionnaires. The manner of grouping is defined in the main text. Seven large sectors were used. Trips were grouped by origins and destinations to these zones for before and after questionnaires. The resulting route changes during the peak period were then studied in the light of the effect of origin and destination on flexibility of route choice.

APPENDIX C

BIBLIOGRAPHY

References in the following pages apply to the various phases of the study. The material that has been annotated is related to the first-stage research on this project. Pertinent data not available for review were also included. Chicago area libraries, the Bureau of Public Roads library in Washington, D. C., and contributions by authors and universities were the main sources of information.

This bibliography is comprised of two parts. The first is a list of publications and annotations arranged under subject headings in alphabetical order by author or, if there was no author, by the title. Items are numbered consecutively within each section. The second part is an alphabetical author index.

I. YIELD SIGNS

1.01 BERRY, D. S., "Research on Use of Right-of-Way Signs." Inst. of Transportation and Traffic Engineering, 1950, Univ. of California, Berkeley, 3 pp. (mimeo.).

1.02 BERRY, D. S., and KELL, J. H., "Use of Yield Signs." *Traffic Engineering,* Vol. 26, No. 4, pp. 154, 156-159 (Jan. 1956).

A summary was made of some of the information available on the use of yield signs. Tentative warrants for installation were suggested which would serve until more definite standards could be determined. The warrants dealt mainly with safety, approach speed and relative volumes.

1.03 BOUMAN, M. J., "The Use of Yield Signs and Illuminated One-Way Signs in San Diego." *Traffic Engineering,* Vol. 29, No. 3, pp. 18-23 (Dec. 1958).

1.04 DONIGAN, R. L., and FISHER, E. C., "Legal Aspects of 'Yield Right-of-Way Signs'." *Traffic Digest and Review,* Vol. 2, No. 9, p. 24 (Sept. 1954).

1.05 FAULKNER, Z. A., "Expert Sees Advantages in New Sign." *Cook County Highways,* Vol. III, No. 10, p. 3 (Mar. 1956).

1.06 GURNETT, G. B., "Yield ROW Sign Study, City of Paramount." *Study No. I-60.01,* 4:1 Unpublished 3:27, Los Angeles County Road Dept., Traffic & Lighting Div.

1.07 HARRISON, H. H., "New 'Yield' Sign on Divided Highways." *Cook County Highways,* Vol. III, No. 11, p. 4 (Apr. 1956).

1.08 HARRISON, H. H., "New Yield Sign for Rural State Highways." *Illinois Highway Engineer,* Vol. 8, No. 2, p. 8 (1956).

1.09 HUTCHINSON, A. L., "The Yield Right-of-Way Sign." *Proc.,* Northwest Conference on Traffic Engineering, 1953, pp. 85-86.

1.10 INWOOD, J., and GREEN, H., "The Effect on Traffic of the Yield Sign." *Research Note No. RN/3245/JI.HG.,* Apr. 1958, Dept. of Scientific and Industrial Research, Road Research Laboratory, BU. 437, BR. 565.

The behavior of vehicles emerging from the minor road was studied at 13 pairs of sites with halt (stop) signs and at 15 pairs with slow signs. At one of each pair of sites the existing sign was replaced by a yield sign and further observations were made, the unconverted sites being used for statistical control. The change from halt to yield resulted in highly significant decreases in delay to minor-street vehicles when no traffic was nearby on the major street, whereas no conclusive evidence was found to indicate similar reductions with replacement of slow signs. Yield signs were found to have a negligible effect on the major-road traffic interval which was accepted by the driver on the minor road.

1.11 INWOOD, J., and NEWBY, R. F., "Yield Signs." *Research Note No. RN/3556/JI.RFN.,* Aug. 1959, Dept. of Scientific and Industrial Research, Road Research Laboratory, BR 642.

Describes experience with the yield sign obtained in Great Britain and the U.S.A. Generally, British studies of delay showed a reduction when a halt (stop) sign was replaced with a yield sign, but not when a slow sign was replaced with a yield sign. Accident studies in Britain were insufficient to draw any conclusions. A review of U.S.A. experience showed that little change in accident experience occurred when a yield sign replaced a stop sign but that yield signs helped cut accidents at formerly uncontrolled intersections.

1.12 INWOOD, J., and NEWBY, R. F., "Yield Signs." *The Surveyor,* Dec. 19, 1959.

Reports a British study of the replacement of halt and slow signs with yield signs. It concluded that drivers treat the yield signs much the same as slow signs and that there was little change in accident frequency with the change in control.

1.13 KELL, J. H., "The Development and Application of Yield Right-of-Way Signs." *Research Report No. 27,* Jan. 1958, Inst. of Transportation and Traffic Engineering, University of California, Berkeley.

Reviews the history of the development and application of the modern yield sign. The major conclusion is that the yield sign is an effective device for controlling traffic at many intersections if it is properly utilized, if it is understood by the public, and if there is reasonable enforcement.

1.14 KELL, J. H., "Application of Yield Right-of-Way Signs." *Traffic Engineering,* Vol. 28, No. 10, pp. 18-22 (July 1958).

Summarizes various applications of yield signs throughout the United States.

1.15 KELL, J. H., "Yield Right-of-Way Signs: Warrants and Applications." *Proc.,* Inst. of Traffic Engineers, 1959, pp. 168-175.

Presents some current thinking on the general subject of yield signs.

1.16 KELL, J. H., "Yield Signs: Warrants and Applications." *Traffic Engineering,* Vol. 30, No. 7, pp. 15-17 (Apr. 1960).

Traffic volumes, approach speed, sight distance and accidents are analyzed singly and warrants for the application of yield signs are suggested or rejected in each of these categories. A listing is made of policy statements and uses for the yield sign.

1.17 NEWBY, R. F., "The Effect of the Yield Sign on Accident Frequencies." *Research Note No. RN/3438/RFN,* Apr. 1959, Dept of Scientific and Industrial Research, Road Research Laboratory, BR. 612.

The effect of the yield sign on the frequency of accidents was investigated at a sample of junctions. In most cases, the new sign replaced existing halt (stop) or slow signs. There were no significant changes attributable to the yield sign except in one area where there appeared to be a tendency toward fewer accidents involving vehicles other than those emerging from the road affected by the sign. The severity of the injury accidents at each group of sites remained virtually unchanged.

1.18 O'CONNELL, R. C., "Experience with Yield Signs." *Traffic Engineering,* Vol. 27, No. 1, p. 34 (Oct. 1956).

1.19 PRISCH, C. W., "Frankly Speaking." *Traffic Engineering,* Vol. 25, No. 4, p. 135 (Jan. 1955).

1.20 RICE, P. W., "The 'Yield Right-of-Way' Sign." *Traffic Quarterly,* Vol. VI, No. 1, pp. 51-58 (Jan. 1952).

Yield signs were placed at five intersections in Tulsa, Okla. Vehicles were checked for approach speed reaction to the sign, and their continued activity across the intersection. It was found that 94.6 percent of the vehicles going through the yield sign were not required to stop by the cross traffic. It was concluded that although yield signs are not the entire answer for the operation of an intersection, it is a step forward.

1.21 RICE, P. W., "The Yield Sign." *National Safety Transactions,* Vol. 32, pp. 78-84 (1953).

1.22 RICE, P. W., "The Yield Sign: Will It Reduce Stop Sign Nuisance." *Public Works,* Vol. 85, No. 10, pp. 91-92 (1954).

1.23 RIGGS, C. E., "A First for Tulsa—The Yield Right-of-Way Sign." *Traffic Review,* Vol. 5, No. 2, pp. 2-3, 37 (Winter 1951).

1.24 "Right-of-Way Violations." *Traffic Digest and Review,* Vol. 8, No. 8, pp. 4-8, 26-29 (Aug. 1960).

Describes and defines various laws and methods dealing with problems and guides for enforcement of right-of-way violations.

1.25 "Second Report on the Yield Sign." Inst. of Traffic Engineers, Comm. on Warrants For and Experiences With Yield Signs, Aug. 1955, 3 pp. (mimeo.)

1.26 STEWART, A. L., "Developments in Yield Right-of-Way Signs." *Proc.,* Sixth California Street & Highway Conf., 1954, pp. 97-98.

1.27 "The Yield Sign in Action." *Traffic Safety,* Vol. 51, No. 4, pp. 20-21 (Oct. 1957).

A before-and-after study was made of a route in Providence, R. I., along which 25 of 27 intersections were changed from uncontrolled and two-way stop-controlled conditions to yield control. Results showed that where the change was from no control to yield, accidents were reduced. The author concludes that the driving public can save time and money by driving on yield-controlled streets.

1.28 "Third Report on the Yield Sign." Inst. of Traffic Engineers, Comm. on Warrants For and Experiences With Yield Signs, July 1956, 7 pp. (mimeo.)

1.29 WILEY, C. C., "Yield Signs." Urbana, Ill., June 1954, 5 pp. (mimeo.)

1.30 WOODLING, H. B., "Yield Right-of-Way Signs." *Proc.,* Inst. of Traffic Engineers, Discussion of Joint Committee on Uniform Control Devices, 1954, pp. 132-134.

II. STOP SIGNS

2.01 BERRY, D. S., "Improve Traffic Control on Through Streets." *Public Safety,* Vol. 13, No. 1, pp. 30-31 (July 1937).

Urges alteration of the present system of traffic regulation, mainly on the through streets which warrant the over-use of stop signs. Steps are also suggested to permit more uniform speeds on streets.

2.02 BISSELL, H. H., "Traffic Gap Acceptance From a Stop Sign." Graduate Research Report, 1960, Unpublished, Inst. of Transportation and Traffic Engineering, University of California, Berkeley.

2.03 BLONSTEIN, H., and GURNETT, G. B., "Before & After Study of Recently Signalized Four-Way Stops." *Study No. 1-59-06 21,* Unpublished 4:10, Los Angeles Road Dept. Traffic & Lighting Div.

2.04 BLUNDEN, W. R., CLISSON, C. M. and FISHER, R. B., "Distribution of Acceptance Gaps for Crossing and Turning Maneuvers." *Proc.,* Australian Road Research Board, Vol. 1, Part 1, Paper No. 11, pp. 188-205 (1952).

Describes a study of gap acceptance characteristics at several intersections. Uncontrolled and stop sign conditions were both studied. A theoretical distribution was fitted to the results of the field study and a delay formula was derived. Results showed that gap acceptance characteristics of drivers who stop are more variable than those not stopping. Critical or minimum gap distributions were fitted with an Erland distribution of varying *K*-value with fairly good accuracy.

2.05 BROWN, L. R., "The Traffic Signal vs the Full Stop at Outlying Intersections." *Proc.,* Inst. of Traffic Engineers, 1932.

2.06 COOPER, B. K., "A Supplementary Legend at Four-Way Stop Intersections." M. S. Thesis, Aug. 1957, Purdue University.

The study was an attempt to determine whether the efficiency of four-way stop intersections could be improved with the addition of the supplementary legend "4-WAY" on the standard stop sign. Results showed drivers accept a lower critical lag with the supplementary message.

2.07 DIER, R. D., "The Four-Way Stop Control." *Proc.*, California Traffic and Safety Conf., 1950, pp. 48-49.

2.08 "Driver Observance of Stop Signs." *Manual of Traffic Engineering Studies,* 1945, National Conservation Bureau, New York, pp. 24-26.

2.09 ELIOT, W. G., "Types of Regulation Affect Driving Habits." *Civil Engineering,* Vol. 5, No. 9, pp. 528-531 (1935).

The behavior of vehicles as affected by several types of regulations was studied. Results show a high percentage of drivers ignore signs such as speed limit, caution and stop signs.

2.10 ERICKSEN, E. L., "Traffic Performance at Urban Street Intersections." *Traffic Quarterly,* Vol. 1, No. 3, pp. 254-267 (July 1947). See Ref. 2.13.

2.11 FISCHER, C. F., *Traffic Survey, Akron, Ohio.* 1934-1935, pp. 69-73.

A section of the report deals with driver observance at stop signs. Vehicles were studied approaching stop signs at 60 intersections. Analysis is given of data on vehicles stopping at or entering the intersection at various rates of speed.

2.12 GAGNON, C. Y., "Effect of Size of Gaps in Line on Acceptance of the Lag at a Stop Sign." M.S. Thesis, June 1962, Northwestern University.

The effect of size of gaps in a line on acceptance of the lag at a two-way stop sign was evaluated. It was found that for a given lag size the acceptance is not greater when there is a line of vehicles on the main street than when there is only one car visible to the side-street driver.

2.13 GREENSHIELDS, B. D., SCHAPIRO, A. B., and ERICKSEN, E. L., "Traffic Performance at Urban Street Intersections." *Technical Report No. 1,* 1947, Yale Bureau of Highway Traffic, Yale University, 152 pp.

A preliminary exploration into the fundamental relationships which exist between traffic units. Field methods and vehicle acceleration and deceleration are discussed. A technique of time spacing analysis is applied to traffic behavior at non-controlled intersections. The application of the Poisson theory to vehicular traffic is demonstrated. Mathematical principles used to check physical phenomena increase the reliability of the values and magnify their possible use.

2.14 HALL, E. M., "Intersection Delay—Signal vs Four-Way Stop." *Proc.,* Inst. of Traffic Engineers, 1952, pp. 60-64.

This study compared delay of two control devices (semi-traffic-actuated signal vs four-way stop control) on the average vehicle passing through an intersection. It was found that (a) some drivers may prefer a signal control even though the delay is greater; (b) the average delay per minor-street vehicle was significantly greater with the semi-actuated signal control than the four-way stop control for all volumes studied; and (c) the average delay per major-street vehicle was significantly greater with a semi-actuated control for all volumes above 800 vph on the studied approaches.

2.15 HANSON, D. J., "Are There Too Many Four-Way Stops?" *Traffic Engineering,* Vol. 28, No. 2, pp. 20-22, 42 (Nov. 1957).

All stop sign locations in Peoria, Ill. were reviewed in an effort to reduce the number of unwarranted signs. After a detailed study of four-way stop intersections, warrants were suggested pertaining to minimum vehicular volume, accident hazard, and maximum vehicular volume. Advantages and disadvantages of four-way stops were discussed. Circumstances under which it is not desirable to install four-way stops were also listed. It was concluded from experience in Peoria that four-way stop signs do serve as useful traffic control devices when properly applied.

2.16 HANSON, D. J., "Over-Controlled Traffic." *Traffic Digest and Review,* Vol. 8, No. 8, pp. 14-18 (Aug. 1960).

Underlines the problem of over-controlled traffic by excessive and unrealistic regulation of motor vehicles, which creates movements that waste money, cause driver confusion, and expose drivers to serious hazards.

2.17 HARRISON, H. H., "Four-Way Stops." *Traffic Engineering,* Vol. XIX, No. 5, pp. 212-214 (Feb. 1949).

Describes experience in Illinois with stop signs and suggests warrants for installation of four-way stop signs.

2.18 HARRISON, H. H., "Four-Way Stop Control." *Papers and Discussions, Convention and Group Meetings,* 1957, American Association of State Highway Officials, pp. 177-182.

2.19 HEBERT, J., "A Study of Four-Way Stop Intersection Capacities." M.S. Thesis, June 1962, Northwestern University.

Three right-angle intersections in the Chicago metropolitan area were used to determine the capacity of four-way stop intersections under various traffic and operating conditions. Data were collected using time-lapse photography. The results indicate that (a) left turns have no effect on the headway of departure, whereas right turns do; (b) right turns increase intersection capacity; (c) longer headways are needed to cross a four-lane vs a two-lane cross street; and (d) 70 percent of vehicles were found to be moving out two abreast if there are two lanes on a loaded approach. Discharge times were calculated for various conditions. A trial capacity chart for four-way stop intersections is presented.

2.20 "Illinois Traffic Engineer Designs a Hooded Stop Sign." *Traffic Digest and Review,* Vol. 2, No. 7, p. 18 (July 1954).

2.21 JACKMAN, W. T., "Driver Obedience to Stop and Slow Signs." *Bull. 161,* Highway Research Board, pp. 9-17 (1957).

A study was made of the effectiveness of reflectorized red and white stop signs compared with those which are enameled yellow and black. The effectiveness of slow signs was also studied. The conclusions tend to indicate that (a) no combination of stop sign and position is any more effective than another as far as driver obedience is concerned; (b) slow signs are, in

themselves, generally not effective; and (c) slow signs should not be used without additional signs stating the nature of the danger involved.

2.22 KENEIPP, J. M., "Efficiency of Four-Way Stop Control at Urban Intersections." *Traffic Engineering,* Vol. XXI, No. 9, pp. 305-306 (June 1951).

Reports a study in Champaign-Urbana, Ill., to evaluate what happens to the efficiency of an intersection control. It was concluded that under no condition can an urban intersection operating as a four-way stop be more efficient than it would be under normal two-way stop control.

2.23 LELAND, E. J., "Four-Way Stop Sign System." *Proc.,* Road Builders Clinic, State College of Washington, Pullman, 1958, pp. 29-31.

2.24 MARKS, H., and HUTCHINSON, A. L., "Warrants for Four-Way Stops." *Proc.,* Northwest Traffic Engineering Conf., 1959, pp. 101–106.

A special committee report is given listing the results from the paper of Daniel Hanson in the Nov. 1957 issue of *Traffic Engineering* (Ref. 2.15). The discussion concluded that an objective study should be extended to include all intersection traffic control devices so as to ultimately delineate the effective areas of influence for each device.

2.25 McCOY, G. T., "The Problems Connected with Traffic Signs." *The Siren,* Municipal Motorcycle Officers of California, Official Year Book, 1957, pp. 41, 145, 147, 149.

2.26 MCEACHERN, C., "A Four-Way Stop Sign System at Urban Intersections." *Traffic Quarterly,* Vol. III, No. 2, pp. 128-137 (Apr. 1949).

Summarizes information dealing with various aspects of four-way stop sign control throughout the United States.

2.27 McINTYRE, L. W., "Report of Committee on Traffic Engineering." *Trans.,* National Safety Council, Vol. 23, pp. 38-39 (Oct. 1933).

2.28 "Minor Intersection Traffic Control by Signs or Traffic Beacons." *Proc.,* Northwest Traffic Engineering Conf., 1953, pp. 84-98.

2.29 MORRISON, R. L., "Comparative Efficiency of Stop Signs and Stop-and-Go Signs at Eight Traffic Intersections." *Proc.,* Inst. of Traffic Engineers, 1931, pp. 39-49.

2.30 PETERSON, S. G., "Control Devices for Blind Intersecsections." *Traffic Engineering,* Vol. 31, No. 1, Part I, pp. 54, 56 (Oct. 1960).

2.31 RAFF, M. S., "Space-Time Relationships at 'Stop' Intersections." *Proc.,* Inst. of Traffic Engineers, pp. 42-49 (1949).

2.32 RAFF, M. S., "A New Study of Urban Signs: A Volume Warrant." *Traffic Quarterly,* Vol. IV, No. 1, pp. 148-158 (Jan. 1950).

2.33 RAFF, M. S., "A Volume Warrant for Urban Stop Signs." ENO Foundation for Highway Traffic Control, 1950, 121 pp.

The research was devoted to developing a volume warrant for installing two-way stop signs at right-angle crossings in urban and in isolated areas not a part of a through street system. By paraphrasing the *Manual of Uniform Traffic Control Devices* volume warrant for fixed-time signals, the following warrant was derived: "A stop sign is warranted, under the criterion of percent delayed, if an average day contains 8 hr during which the volumes are such as to delay at least 50 percent of the side-street cars." The warrant was intended to supplement other warrants. In addition to the volume warrant, the principal study findings are (a) definition of the "critical lag" and the fact that it varies from one intersection to another; (b) the average length of delay of side-street cars does not correlate well with traffic volumes and is, therefore, not a good basis for a sign warrant; and (c) that mathematical theory can be applied to stop control, but there remains the additional problem of taking adequate account of the sluggish starting of a line of stopped cars.

2.34 "Required Stops." *Publication No. 2541,* Northwestern Traffic Inst., 17 pp.

This basic training manual is one of a series on Traffic Law Enforcement developed by the staff of the Traffic Institute specifically for use in departmental training programs. Written at the operational level, it provides detailed instructions on the procedures a police officer should follow in enforcing laws of required stops.

2.35 SAWHILL, R. B., "The Stop Sign." *Proc.,* Northwest Conf. on Traffic Engineering, 1953, pp. 87-90.

2.36 "Sign Moves to Keep Up With the Times." *Cook County Highways,* Vol. IX, No. 10, pp. 5-6 (Feb. 1962).

2.37 SMEED, R. J., "Road User Behavior in Relation to Road Conditions." *Traffic Engineering,* Vol. 25, No. 9, pp. 361-365 (June 1955). See Ref. 3.57.

2.38 SWERDLOFF, C. N., "A Study of Gap Acceptance at a Stop Sign Location." M.S. Thesis, June 1962, Northwestern University, 72 pp.

The object of the study was to evaluate the possible effects of main-street width and peak and off-peak traffic conditions upon the gap acceptance characteristics of drivers entering stop-sign-protected intersections. The conclusions indicate that (a) the gap acceptance distribution of peak-hour drivers tends to be more uniform than for drivers in off-peak hours; (b) for a given gap size, the probability of acceptance appears to be greater during peak-hour than off-peak hours. These results are independent of main-street width; and (c) the lack of correlation that was found between main-street width and gap acceptance may be a result of the "creep phenomenon."

2.39 "Traffic Signals Versus Stop Signs." *Street Engineering,* Vol. 1, No. 6, p. 28 (June 1956).

2.40 WILKIE, L. G., "58,732 Motorists Checked at Stop Signs." *Cook County Highways,* Vol. 1, No. 10, pp. 4-5, 7 (Mar. 1954).

A study of driver obedience to stop signs in Cook County, Ill. Almost 20 percent of the drivers observed failed to stop at the sign. It was decided to

employ selective enforcement and thoroughly review the problem.

2.41 WILKIE, L. G., "Further Study of Stop Sign Disobedience." *Cook County Highways*, Vol. II, No. 2, pp. 6-7 (July 1954).
Further evaluation of data obtained by checking 58,732 motorists at stop signs in Cook County, Ill.

III. PEDESTRIAN CONTROLS

A. School Crossing Protection

3.01 "A Program for School Crossing Protection." *Inst. of* Traffic Engineers, Aug. 1962.

3.02 BATTS, H., "Design, Installation and Use of School Crossing Signals." *Proc.*, Inst. of Traffic Engineers, Paper No. 1, pp. 263-264 (1963).

3.03 CRAWFORD, G. L., "Design, Installation and Use of School Crossing Signals." *Proc.*, Inst. of Traffic Engineers, Paper No. 2, pp. 264-269 (1963).

3.04 DIER, R. D., "Determining the Degree of Hazard at School Crossings." *Traffic Engineering*, Vol. 25, No. 4, pp. 137-139, 153 (Jan. 1955).

A technique is described for determining whether the traffic stream at a particular school crossing has adequate and frequent gaps. The author states that the method appears to have the simplicity and accuracy that would encourage its adoption as a uniform method for the determination of the degree of hazard at school crossings.

3.05 DIER, R. D., "School Crossing Protection." *Proc.*, Inst. of Traffic Engineers, Report of Committee 3B, 1958, pp. 94-96.

3.06 HAVENNER, J. E., "Protection at School Crossing." *Proc.*, Sixth California Street and Highway Conf., Feb. 1954, pp. 84-91.

A discussion of the various problems involved in obtaining proper and adequate protection controls at school crossings. The author attempts to delineate the respective areas of responsibility of the home, education, enforcement, and engineering.

3.07 HOWIE, G. W., "Effective Protection for School Crossings." *Proc.*, Inst. of Traffic Engineers, 1950, pp. 72-77.

3.08 INST. OF TRAFFIC ENGINEERS, "Report of the Committee on School Crossing Protection." *Traffic Engineering*, Vol. 27, No. 11, pp. 530-535 (Aug. 1957).

Reviews policies, warrants and methods used by various traffic authorities throughout the United States. Several graphs are included which analyze school crossings for traffic controls.

3.09 KUEHL, R. E., and SEBURN, T. J., "School Crossing Warrants Protect Kansas City." *Traffic Quarterly*, Vol. X, No. 3, pp. 398-415 (July 1956).

Numerical rating systems were developed to evaluate intersections in Kansas City, Mo. The system indexed need for either a school stop sign, a pedestrian-actuated signal, or a school patrol officer at school crossings. In practice the systems gave good indication of what kind of control was needed.

3.10 LAWTON, L., "Traffic Controls in the Vicinity of School Zones." *Traffic Engineering*, Vol. 24, No. 7, Part II, pp. 239-241, 244 (Apr. 1954).

Location of crossings, warrants, school traffic signals, persons at crossings, selection of positive control and setting up a program were discussed in hopes of establishing a sensible and uniform approach to the school crossing problem.

3.11 "School Crossing Protection." California Division of Highways, Sacramento, 1953.

3.12 SIELSKI, M. C., "School Crossing Protection." *Traffic Engineering*, Vol. 25, No. 12, pp. 494-497 (Sept. 1955).

Describes the method used in the Chicago area for carrying out school crossing protection programs. This includes (a) analysis of hazardous crossings on a city-wide basis; (b) the representation of various interested groups to conduct the study; and (c) the presentation of a report at a public meeting.

B. Scramble System

3.13 BOYES, R. C., "Pedestrian Phasing Signals." *Proc.*, Northwest Traffic Engineering Conf., 1958, pp. 110-112.

3.14 BUTLER, E. L., "Denver's New Traffic Control System Includes Pedestrian Separation Period." *Traffic Digest and Review*, Vol. 1, No. 1, pp. 16-18 (Apr. 1953).

3.15 CAL Y MAYOR, R., "The Effect of Pedestrian Signals on Vehicular Traffic." *Traffic Engineering*, Vol. XXI, No. 7, pp. 232-235 (Apr. 1951).

A before-and-after study of vehicle performance at intersections was made. The intersections were studied when there were regular traffic signals and, four months later, after pedestrian signals were installed. Pedestrian-vehicle conflicts were drastically reduced, allowing a notable time reduction for turning movements. The capacity of the intersection was decreased due to the reduction of green time per phase.

3.16 DIER, R. D., "Pedestrian Scramble Control." *Traffic Engineering*, Vol. 24, No. 11, pp. 413-414 (Aug. 1954).

Describes the installation and successful operation of scramble control at an intersection in Long Beach, Calif.

3.17 DIER, R. D., "Warrants for the 'Scramble' System of Traffic Signal Control." *Proc.*, Seventh California Street and Highway Conf., Feb. 1955, pp. 79-82.

The turning warrant, accident-hazard warrant, pedestrian warrant, and various factors which limit the value of warrants were discussed. The author cautions that factual engineering studies and careful analysis should be made before applying the scramble system.

3.18 FAUSTMAN, D. J., "Pedestrian-Phased Traffic Signals (Scramble System)." *Proc.*, Sixth California Street and Highway Conf., Feb. 1954, pp. 93-96.

Discusses the scramble system as applied in Sacramento, Calif. Conclusions indicate that (a) the system

should be used only at locations where there is considerable conflict between pedestrians and turning vehicles which results in undue delay to vehicle movement; (b) the system will cause much less congestion if it is possible to alter the time of the signals at various times of day; and (c) it appears to function more satisfactorily on one-way streets than on two-way streets.

3.19 HALEY, C. E., "Scramble, Scramble, Who's Got Scramble?" *Traffic Engineering,* Vol. 28, No. 8, pp. 18-20, 44 (May 1958).

To familiarize traffic engineers with the practice elsewhere, questionnaires were sent to various cities in an attempt to find out which cities were using the scramble system, which had used it and discontinued it, and which were not using it. The results were presented in several tables.

3.20 HICKS, J. V., "Scramble Traffic." *Police Chief,* Vol. XX, No. 5, pp. 4-6 (May 1953).

3.21 MARCONI, W., "Exit Scramble in San Francisco." *Traffic Engineering,* Vol. 29, No. 4, pp. 20-22, 35 (Jan. 1959).

The increasing traffic volumes and congestion in downtown San Francisco and the need for increased capacity prompted the removal of the existing pedestrian phase or "scramble" from four signalized intersections. Before-and-after studies indicate a net gain of 24 percent in traffic speeds after the removal of the scramble system.

3.22 O'CONNOR, T. J., "Scramble System in Boston." *Traffic Engineering,* Vol. 28, No. 11, p. 37 (Aug. 1958).

3.23 "Scramble System—Some Like It." *Street Engineering,* Vol. 3, No. 12, p. 20 (Dec. 1958).

3.24 SHOAF, R. T., and MARCONI, W., "Scramble in San Francisco." *Traffic Engineering,* Vol. 25, No. 2, p. 53-57 (Nov. 1954).

Discusses the before-and-after studies of four San Francisco intersections, appraising the effect of the scramble system. The conclusions point out that although pedestrian and motorist reaction was favorable, vehicular travel time on streets through the system increased by 11.7 to 94.4 percent.

3.25 SHOAF, R. T., "A Discussion of Warrants for Scramble Signals." *Traffic Engineering,* Vol. 25, No. 7, pp. 261-263 (Apr. 1955).

Several intersections were studied and a formula was developed which rated the effectiveness of the scramble system at San Francisco intersections. It was concluded that the scramble system causes added delay and economic loss to the motorist and is not the answer to making better use of existing streets.

C. General

3.26 ALLEN, B. L., "Pandas versus Zebras; Comparative Study of Control at Pedestrian Crossing." *Traffic Engineering and Control,* Vol. 4, No. 11, pp. 616-619 (Mar. 1963).

3.27 BARTON, G. W., "Pedestrian Signal Control." *Traffic Digest and Review,* Vol. 2, No. 5, pp. 8-13 (May 1954).

Discusses various aspects of the scramble system as experienced in Milwaukee, Wis., and Evanston, Ill. Among the conclusions, it was found that the scramble system cannot be depended upon to improve the movement of both vehicles and pedestrians under all circumstances.

3.28 BERRY, D. S., "Proposed Change in Pedestrian Right-of-Way at Non-Signalized Intersections." Proposals for Modification in the Report of the Subcommittee on the Rules of the Road, Mar. 1962, 3 pp.

3.29 "British Pedestrian Security." *Street Engineering,* Vol. 1, No. 8, p. 20 (Aug. 1956).

3.30 BRUENING, M. E., "Separate Walkers and Right-Turners." *Traffic Engineering,* Vol. 28, No. 1, pp. 39-40 (Oct. 1957).

A system is described where right turns are allowed during the first 15 sec of the signal cycle, during which time pedestrians do not walk. During the remainder of the green interval, pedestrians walk parallel to the traffic streams but motorists cannot turn right.

3.31 DAVRI, D. P., "New Safety Pedestrian Crossing." *Road Safety in Indiana,* July-Sept. 1959.

3.32 DUFF, J. T., "Mutual Obligations of Turning Traffic and Pedestrians at Signal Controlled Intersections and Appropriate Indication Thereof." *International Road Safety and Traffic Review,* Vol. XI, No. 2, pp. 9-10, 12, 14-16 (Spring 1963).

A general discussion of eight papers written about turning traffic and pedestrians at signal-controlled intersections. To ascertain current practice, questionnaires about the control of pedestrians with traffic light signals were received from 16 European countries, the U.S.A., and Israel. The results are tabulated.

3.33 DUNN, J. B., "Pedestrian Footbridges." *Research Note No. RN/2036/JBD,* 1953, Road Research Laboratory, 5 pp.

3.34 GROVE, A. W., "Pedestrian Signal Warrants." *Proc.,* Inst. of Traffic Engineers, 1958, pp. 97-99.

3.35 HAYES, A. T., "Pedestrian Control." *Proc.,* Inst. of Traffic Engineers, 1961, pp. 87-92.

The program of pedestrian control applied in Lansing, Mich., is described. Several graphs tabulate results of before-and-after studies.

3.36 HICKY, N. W., "Public Likes 'Don't Leave Curb.'" *American City,* May 1957, pp. 165-166.

3.37 HOFFMAN, L., "Hammond's New Pedestrian Signals." *Traffic Digest and Review,* Vol. 3, No. 6, p. 7-8 (June 1955).

3.38 HOFFMAN, L., "Pedestrian Signal." *Traffic Engineering,* Vol. 25, No. 12, pp. 492-493 (Sept. 1955).

3.39 LAWTON, L., "Lawton Pedestrian Signal." *Traffic Engineering,* Vol. 25, No. 12, pp. 490-491 (Sept. 1955).

3.40 LEE, D. M., "Portland Protects Its Pedestrians." *Traffic Quarterly,* Vol. VI, No. 3, pp. 284-293 (July 1952).

The procedure followed by Portland, Ore., to reduce pedestrian accidents is described. The program of pedestrian protection was successfully achieved by a

balanced program of education, enforcement, and engineering.

3.41 MARSH, B. W., "Pedestrian Research." *Proc.*, Highway Research Board, Vol. 19, pp. 340-346 (1939).

3.42 MARSH, B. W., "What About the Pedestrian?" *Proc.*, Inst. of Traffic Engineers, 1950, pp. 28-41.

3.43 MASSEY, S. A., "Mathematical Determination of Warrants for Pedestrian Crossings." *Traffic Engineering*, Vol. 32, No. 12, pp. 19-21 (Sept. 1962).

3.44 MOHLE, R. H., "Crosswalk Marking Practices and Driver and Pedestrian Behavior at Two Different Crosswalk Markings." Master of Engineering Thesis, Nov. 1958, University of California, Berkeley, 21 pp.

Presents the results of a questionnaire survey concerning crosswalk marking practices in the United States. A field study compared the operational characteristics of a crosswalk marked with standard and zebra configurations. Results indicated that (a) there was a significant increase in the proportion of yielding drivers with the zebra markings; and (b) pedestrian crossing speeds and their acceptance of vehicle gaps did not significantly change when the crosswalk marking was redesigned.

3.45 MOORE, R. L., "An Advanced Warning Sign at Pedestrian Crossings." *Research Note No. RN/1396/RLM*, 1950, Road Research Laboratory, 8 pp.

3.46 "Pedestrian Can Turn Traffic Light Green." *Traffic Engineering*, Vol. 28, No. 7, p. 23 (Apr. 1958).

3.47 "Pedestrian Control: Key To City Traffic Problem." *Traffic Safety*, Vol. 51, No. 3, pp. 40-41 (Sept. 1957).

3.48 "Planned Pedestrian Program." American Automobile Association Foundation for Traffic Safety, Washington, D.C., Mar. 1958, 163 pp.

3.49 RAY, H. E., "Responsibility for Pedestrian Protection at Signalized Intersections." *Proc.*, Western Section, Inst. of Traffic Engineers, 1955, pp. 147-150.

3.50 REEDER, E. J., "What Can We Do About Pedestrian Accidents?" *Proc.*, Highway Research Board, Vol. 18, Part I, pp. 387-392 (1938).

3.51 ROBINSON, C. C., "Pedestrian Interval Acceptance." *Proc.*, Inst. of Traffic Engineers, 1951, pp. 144-150.

A study was made on two-lane urban intersections, one in Milford and one in New Haven, Conn. The basic objective was to answer the question, "What advantage in time or distance does the average pedestrian require before crossing in front of a vehicle?" Pedestrian behavior data pertaining to these intersections are tabulated.

3.52 ROBINSON, J. H., "Mid Block Pedestrian Crossing in Oklahoma City," *Traffic Digest and Review*, Vol. 4, No. 4, pp. 20-24 (Apr. 1956).

3.53 ROUSEL, S., "The Pedestrian Problem." *Law and Order*, Vol. 10, No. 2, pp. 14-16 (Feb. 1962).

3.54 RUDDEN, J. B., "Warrants For and Experience With Pedestrian Intervals at Signalized Intersections." *Proc.*, Inst. of Traffic Engineers, Report of Committee 4E, 1959, pp. 181-182.

Concurrent pedestrian indication, exclusive pedestrian phase, and clear pedestrian interval were defined and conditions of application were noted.

3.55 SIEGEL, S. T., "The Role of Pedestrian Control in Traffic Regulation." *Proc.*, Inst. of Traffic Engineers, 1961, pp. 72-80.

Discusses the problem of pedestrian control, emphasizing that the pedestrian element in the traffic stream be recognized and treated as a separate and important entity.

3.56 SINGER, R. E., "Action for Pedestrian Safety and Control." *International Road Safety and Traffic Review*, Vol. XI, No. 4, pp. 17-20, 22 (Autumn 1963).

3.57 SMEED, R. J., "Road User Behavior in Relation to Road Conditions." *Traffic Engineering*, Vol. 25, No. 9, pp. 361-365 (June 1955).

Presents the results of a study of pedestrian behavior and driver behavior in England. It is concluded that if you want pedestrians to use a traffic facility, you must make it easy for them. Pedestrian gap acceptance is also plotted. Several charts show the speed of approach and stop obedience at intersections with halt signs, slow signs, or no control. It was found that the halt sign does some good, although it is not universally respected. Driver obedience, however, can be increased by making the signs more conspicuous.

3.58 "Spaced Bar Strip More Visible at Pedestrian Crossings." *Traffic Digest and Review*, Vol. 1, No. 1, p. 13 (Apr. 1953).

3.59 STONEY, L. H., "New Street Marking System Controls Pedestrian Traffic." *Traffic Engineering*, Vol. 25, No. 1, pp. 32, 34 (Oct. 1954).

Michigan City, Ind., supplemented existing green walk signals and red wait signals with crosswalks painted a bright green. The results indicated a high degree of pedestrian and driver observance.

3.60 "Study of Pedestrian Habits at Street Intersections." *University of California Highway Research Series 1*, No. 1, pp. 25-26 (1949-1950).

3.61 SYREK, D., and CHIN, G., "Effect of Signals on Pedestrian Accidents At and Between Major-Minor Intersections." *Study No. P53-06-21*, Unpublished 5:14, Los Angeles County Road Dept., Traffic & Lighting Div.

3.62 TANNER, J. C., "The Delay to Pedestrian Crossing a Road." *Research Note No. RN/1428/JCT*, 1950. Road Research Laboratory, 11 pp.

3.63 "The Sharing of the Green in Los Angeles." *American City*, October, 1958, p. 145.

3.64 UTTER, R. F., "The Influence of Painted Crosswalks on the Behavior of Pedestrians." Unpublished Ph.D. Dissertation, Dept. of Psychology, University of California, Los Angeles.

3.65 VON STEIN, W., "The Problem of Pedestrian Signalization." *International Road Safety and Traffic Review*, Vol. X, No. 4, pp. 41, 43-45 (Autumn 1962).

3.66 WHEDON, B., "Pedestrian and Turn Controls in Downtown Omaha." *Traffic Digest and Review*, Vol. 3, No. 9, pp. 6-8 (Sept. 1955).

IV. TURN CONTROLS

4.01 ARCHER, J. G., HALL, R. I., and EILON, S., "Effect of Turning Vehicles on Traffic Flow Through a Signal Controlled Junction." *Traffic Engineering & Control,* Vol. 5, No. 5, pp. 295-297 (Sept. 1963).

4.02 BERRY, D. S., SCHWAR, J. F., and WATTLEWORTH, J. N., "Evaluating Effectiveness of Lane Use Turn Control Devices." *Proc.,* Highway Research Board, Vol. 41, pp. 495-528 (1962).

4.03 BLACKBURN, J. B., "A Study of Delay at Intersections for Turning Vehicles." Presented at 42nd Annual Meeting, Highway Research Board, 1963.

Delay to turning vehicles at signalized and non-signalized intersections was compared with through vehicles for the purpose of developing penalties to be used in computer assignment. A moving-car technique was used in combination with a continuously moving tape recording device. Results showed delay to left turns to be significantly greater than through movements, whereas delay to right turns was not significantly greater than through vehicles. Six locations were studied, with 60 observations being made at each. A nested factorial expression was used to describe the data statistically.

4.04 BRAFF, L. M., "Traffic Engineering Techniques Applied in Los Angeles." *Traffic Quarterly,* Vol. X, No. 3, pp. 331-337 (July 1956).

Discusses various methods of increasing capacity along major surface streets in Los Angeles, Calif. The methods used were street markings for turning lanes, signing, turn signals, and vehicle density detectors which illuminated "no left turn" signs when a specific density was reached.

4.05 "Detroit Adopts New Left Turn Control." *Traffic Digest and Review,* Vol. 2, No. 7, p. 18 (July 1954).

4.06 EXNICIOS, J. F., "The Problem of the Signalized Intersection—The Left Turn." *Proc.,* Inst. of Traffic Engineers, 1963, pp. 242-246.

The problem of left-turning vehicles at signalized intersections is discussed with respect to the practice at several intersections in New Orleans, La. Among the methods employed were the actuated left-turn signal and left turns rerouted by means of a mid-block U-turn.

4.07 FAILMEZGER, R. W., "Relative Warrant for Left-turn Refuge Construction." *Traffic Engineering,* Vol. 33, No. 7, pp. 18-20, 50 (Apr. 1963).

From past experience in the investigation for left-turn refuge construction at intersections on the state highways of Oregon, an index of hazard and a relative warrant were derived. These would indicate potential hazard and need by correlating the physical elements, accident records, and the cost of construction at a location being considered for the installation of a left-turn refuge.

4.08 FORBES, T. W., GERVAIS, E. and ALLEN, T., "Effectiveness of Symbols for Lane Control Signals." *Bull. 244,* Highway Research Board, 1960, p. 16-44.

4.09 FOWLER, P. F., "Before and After Study of 12″ Green Signal Arrow." *Proc.,* Northwest Institute of Traffic Engineers, 1959, p. 83.

4.10 GEORGE, L. E., "Characteristics of Left Turning Passenger Vehicle." *Proc.,* Highway Research Board, Vol. 31, pp. 374-385 (1952).

4.11 GRAVER, R. W., "Lane and Turn Controls." *Proc.,* Thirteenth California Street and Highway Conf., 1961, pp. 96-97.

4.12 GURNETT, G. B. and WATSON, L., "Left Turn Protection Effectiveness." *Study No. I 59-06.2,* 21 unpublished, 3:11, 159, Los Angeles County Road Dept., Traffic and Light Div.

4.13 HART, J. W., "Right Turns at Urban Intersections." *Traffic Quarterly,* Vol. III, No. 1, pp. 74-82 (Jan. 1949).

Describes a preliminary study attempting to arrive at a warrant which would be used for restricting the right-turning movement of vehicles during certain hours of the day when vehicle-pedestrian conflict is greatest.

4.14 HAWKINS, H. E., "A Comparison of Leading and Lagging Greens in Traffic Signal Sequence." *Proc.,* Inst. of Traffic Engineers, 1963, pp. 238-242.

A summary of current practice on the use of leading and lagging green intervals as a method of permitting left turns at signalized intersections. Advantages and disadvantages of each are listed.

4.15 INSTITUTE OF TRAFFIC ENGINEERS, Report by Committee 4D (61), "Application of Red and Yellow Arrows as Traffic Signal Indications." *Traffic Engineering,* Vol. 33, No. 12, pp. 42-44, 46, 48-51 (Sept. 1963).

The report attempts to (a) present data on where the applications are being made, (b) categorize the uses and provide typical examples in each category, (c) analyze the present applications, and (d) set forth the requirements for research which would objectively evaluate the use of red and yellow arrows.

4.16 KARMEIER, D. F., "Left Turns at Signalized Intersection." *Proc.,* Inst. of Traffic Engineers, 1963, pp. 247-251.

Summarizes the experience with left-turn policies which have been in effect in the area of St. Louis, Mo. Recommendations concerning left turns at signalized intersections were proposed which emphasized clarity of intent and standardization of control.

4.17 KRAISER, F. J., JR., "Left Turn Gap Acceptance." Study Thesis, 1951, Yale Bureau of Highway Traffic, Yale University.

4.18 LAPLANTE, J. N., "The Effect of Parking at Intersections with Left Turn Channelization." M.S. Thesis, June 1962, Northwestern University, 40 pp.

4.19 MC NAUGHTON, K. A., "Lane Use Control on Urban Thoroughfares." M.S. Thesis, 1958, Purdue University.

4.20 NEWELL, G. F., "The Effect of Left Turns on the Capacity of a Traffic Intersection." *Quarterly of Applied Mathematics,* Vol. 17, No. 1, pp. 67-76 (Apr. 1959).

4.21 PLINE, J. L., "Application of Green Arrows to Signal Indications in Idaho." *Proc.,* Northwest Conf. on Road Building and Traffic Engineering, 1961, pp. 83-98.

4.22 RANKIN, W. W., "Report on Results From Right Turn on Red Light Questionnaire." *Traffic Engineering,* Vol. 26, No. 1, pp. 30, 51 (Oct. 1955).

4.23 RAY, J. C., "The Effect of Right-Turn-On-Red on Traffic Performance and Accidents at Signalized Intersections." Student Research Report, 1956, Inst. of Transportation and Traffic Engineering, University of California, Berkeley, 37 pp.

4.24 RAY, J. C., "Experience With Right-Turn-On-Red." *Proc.,* Inst. of Traffic Engineers, 1956, pp. 111-116.

The research included a questionnaire study, an investigation of accidents at signalized intersections, and a study of delays to right-turn-on-red traffic compared to right-turn-on-green traffic. The results show that right-turn-on-red does not add any significant hazard at signalized intersections and, in fact, has many advantages that tend to decrease delay and increase capacity.

4.25 RICE, P. W., "Effectiveness of Lane Markings on Urban Turning Movements." *Traffic Engineering,* Vol. XX, No. 10, pp. 394-397 (July 1950).

4.26 RISER, C., "Lane Use Controlled at Intersections—Past History and Study Methods." M.S. Thesis, Feb. 1960, Northwestern University.

4.27 SAWHILL, R. B. and NEUZIL, D. R., "Accident and Operational Characteristics on Arterials Utilizing Two-Way Median Left Turn Lanes." *Record No. 31,* Highway Research Board, 1963, pp. 20-56.

This study considered the effect of the two-way median left-turn lane on accident experience along streets serving commercial and industrial areas in Seattle, Wash. Trends in accidents, accident rates, type of motor vehicle collisions, and accident severity were considered. The report indicates that proper use of the two-way median left turn can aid in the reduction of accidents or at least help to attenuate increases in accidents when traffic volume and property development increase.

4.28 SCHWAR, J. F., "Criteria for Determining Effectiveness of Lane Use Controls at Intersections." M.S. Thesis, Feb. 1960, Northwestern University.

4.29 SIMPSON, H. S., "A Method of Facilitating Left Turns." *American City,* Feb. 1926.

4.30 SULLIVAN, T. D., "A Field Evaluation of Alternate Designs of Lane Use Control Signs at Signalized Intersections." M.S. Thesis, Aug. 1961, Northwestern University.

4.31 "Turn Controls in Urban Traffic." ENO Foundation for Highway Traffic Control, 1951, 90 pp.

Discusses and develops a theory on turn controls at intersections and summarizes results of past studies and experiences of communities with various turn controls. A study was carried out investigating the percentage of vehicles delayed due to pedestrian volumes. Length of delay was not recorded. Curves are presented for use in determining a critical point at which turn controls should be applied based on percentage of vehicle turns delayed.

4.32 WILSON, W. B., "Traffic Patterns at Intersections." *Reprint No. 34,* Joint Highway Research Project, July 1948, Purdue University.

V. SIMULATION

A. Intersections and Surface Streets

5.01 AITKEN, J. M., "Simulation of Traffic Conditions at an Uncontrolled T-Junction." *Traffic Engineering & Control,* Vol. 5, No. 6, pp. 354-358 (Oct. 1963).

A model is presented for simulating a T-intersection on a digital computer using an exponential distribution to determine arrival rates from a signal upstream. Gap acceptance is defined as a constant value for each movement. Delay and queue length are shown as a function of the proportion of vehicles moving into or out of the side street.

5.02 BENHARD, F. G., "A Simulation of a Traffic Intersection on a Digital Computer." M.S. Thesis, June 1959, University of California, Los Angeles.

5.03 "City Traffic Simulated by Computer." *Computers and Automation,* May 1962.

5.04 GERLOUGH, D. L. and WAGNER, F. A., JR., "Simulation of Traffic in a Large Network of Signalized Intersections." Presented at Second International Symposium on Theory of Road Traffic, June 1961, London, England, 15 pp.

Describes a macroscopic simulation model for a network of signalized intersections. The model is based on a link, node format. Each node is connected by one or two one-way links, which are in turn segmented into zones. The primary outputs are the total delay incurred on each link, average speed, average delay, average density, average distance traveled, and travel time. The model was tested by field studies to compare travel times, speeds, and volumes. The tests showed the model to be generally realistic.

5.05 GOODE, H. H., POLLMAR, C. H. and WRIGHT, J. G., "The Use of a Digital Computer to Model a Signalized Intersection." *Proc.,* Highway Research Board, Vol. 35, pp. 548-557 (1956).

5.06 GOODE, H. H. and TRUE, W. C., "Simulation and Display of Four Interrelated Vehicular Traffic Intersections." Presented at 13th National Meeting, Association for Computing Machinery, 1958.

5.07 GOODE, H. H. and TRUE, W. C., "Simulation of Four Inter-Related Vehicular Traffic Intersections." Apr. 1, 1958. (mimeo.)

Describes a digital simulation of one signalized intersection and four interconnected intersections in the form of a city block. The model is discussed in detail. Results of the four-intersection simulation are given.

5.08 JORGENSEN, N. O., "Determination of the Capacity of Road Intersection by Model Testing." *Ingenioren,* Vol. 5, No. 3, pp. 99-101 (1961).

5.09 KELL, J. H., "Analyzing Vehicular Delay at Intersections Through Simulation." *Bull. 356,* Highway Research Board, 1962, pp. 28-39.

Describes the development of a simulation model for the intersection of a pair of 2-lane two-directional streets. The model described was developed for analyzing both 2-way stop and signal control. A vehicle generation method and gap acceptance distribution are presented.

5.10 KELL, J. H., "Results of Computer Simulation Studies as Related to Traffic Signal Operation." *Proc.,* Inst. of Traffic Engineers, 1963, pp. 70-107.

5.11 KELL, J. H., "Intersection Delay Obtained by Simulating Traffic on a Computer." *Record No. 15,* Highway Research Board, 1963, pp. 73-97.

This simulation study was concerned primarily with delay experienced at an intersection under stop-sign control, and under fixed-time signal control with two different timing schemes. The major conclusion to be drawn from the results of simulating 40,000 hr of traffic is that intersection delay is increased by the installation of a traffic signal under virtually all of the approach volume conditions studied. A regression analysis failed to show any correlation between total delay and volume factors other than total volumes, at the stop-controlled intersection. It was emphasized that intersection delay should be an important consideration in refining warrants, and other justification should be made when the delay is substantially increased by a signal installed under such warrants.

5.12 LEWIS, R. M., "The Simulation of Vehicular Traffic at an Intersection on a Digital Electric Computer." M.S. Thesis, May 1959, Rensselaer Polytechnic Institute.

5.13 LEWIS, R. M., "The Simulation of Traffic Flow to Obtain Volume Warrants for Intersection Control." *Research Report No. 23,* Ph.D. Dissertation, Sept. 1962, Purdue University.

5.14 LEWIS, R. M. and MICHAEL, H. L., "The Simulation of Traffic Flow to Obtain Volume Warrants for Intersection Control." *Record No. 15,* Highway Research Board, 1963, pp. 1-43.

A mathematical model was developed whereby a traffic intersection under two-way stop, semi-traffic-actuated signal control could be simulated on a digital computer to obtain volume warrants for intersection control. Delay is considered to be the most important factor in determination of the warrants. The results include several charts relating delay and traffic volume considering the critical lag at a stop sign and detector placement at the signalized intersection. The charts generally showed that there are two regions, defined by major- and minor-street volume combinations, such that in each, one control produces more delay than the other. Volume warrant diagrams are exhibited showing (a) points of equal delay for both controls as a function of the traffic volumes on both streets; and (b) for the stop-sign control, the average wait per side-street vehicle as a function of the traffic volume on the two streets.

5.15 MILLER, V. E., "Area Control by Digital Computer." *Traffic Engineering & Control,* Vol. 5, No. 6, pp. 359-365 (Oct. 1963).

Discusses the need for area control of a signal system by digital computer. The method of developing and carrying out such a program is also presented. Also discussed is the simulation technique as applied to analyzing traffic control.

5.16 MORRISON, J. W., JR., and MOORES, C. R., "The Application of Analog Computers to Traffic Intersection Problems." Arizona State University, Dec. 1962, 17 pp. (mimeo.)

Presents the model and results of an analog computer simulation of a signalized intersection. The model was tested using inputs from an existing intersection. The output of the simulation agreed with measures of operation found in the field, within the limits of the accuracy of the assumptions used.

5.17 RHEE, S. Y., "The Urban Traffic Control Simulator." M.S. Thesis, Case Institute of Technology.

5.18 RUITER, E. R. and SHULDINER, P. W., "Operating Costs at Intersections Obtained from the Simulation of Traffic Flow." Presented at 43rd Annual Meeting, Highway Research Board, Jan. 1964, Washington, D. C., 12 pp. and tables.

An intersection simulation routine developed by Lewis and Michael (see Ref 5.14) and a method for determining vehicle operating costs are combined by the authors to derive comparative costs of operation at an intersection with different controls. Two-way stop and fixed-time signal control are compared at varying volumes on major and minor streets. The resulting line of equal costs is shown to compare with the volume warrant found by Michael. It is also shown to closely approximate the warrants found in the *Manual on Uniform Traffic Control Devices.*

5.19 SNELL, J. E., "Simulation of Highway Intersection Performance—A Simplified Example." Nov. 1963. (mimeo.)

Presents a simulation model of an intersection of two one-way streets with a single stop-sign control. The model is described and results exhibited from a short run. The major outputs were volume, delay, and queue length. The simulation was carried out using a constant minimum acceptable gap and then using a distribution. Comparison showed that the constant value resulted in a very optimistic level of operation. The variation of results was about the same for each case.

5.20 STARK, M. C., "Computer Simulation of Traffic on Nine Blocks of a City Street." *Bull. 356,* Highway Research Board, 1962, pp. 40-47.

Describes the method used to simulate the volume and movements of cars with a digital computer using a nine-block-long test site in Washington, D.C., where abundant field data were available for control and checking purposes. Volumes and running times were used as primary output. The system contained signalized and stop-controlled intersections.

B. Freeways and Highways

5.21 BRAND, D., "Freeway On-Ramp Simulation." S. M. Thesis, June 1961, Massachusetts Institute of Technology.

5.22 CASTILLO, P., "Simulation of Weaving Traffic on a Digital Computer." S. M. Thesis, Jan. 1960, Massachusetts Institute of Technology.

5.23 DOUGLAS, R. A. and WALTON, J. R., "The Simulation on a Digital Computer of Rural Highway Configuration and the Movement of Traffic." *Project: ERD-110-F,* Highway Research Program, July 1962, Engineering Research Dept., North Carolina State College, 34 pp.

5.24 GERLOUGH, D. L., "Simulation of Freeway Traffic on a General Purpose Discrete Variable Computer." Ph. D. Dissertation, June 1955, University of California, Los Angeles.

5.25 GERLOUGH, D. L., "Simulation of Freeway Traffic Flow by an Electronic Computer." *Proc.,* Highway Research Board, Vol. 35, pp. 543-547 (1956).

5.26 GERLOUGH, D. L., "Simulation of Freeway Traffic by Digital Computers." *Proc.,* Conf. on Increasing Highway Engineering Productivity, July 1956, Georgia Institute of Technology.

5.27 GLICKSTEIN, A., FINDLEY, L. D. and LEVY, S. L., "Application of Computer Simulation Techniques to Interchange Design Problems." *Bull. 291,* Highway Research Board, 1961, pp. 139-162.

5.28 GLICKSTEIN, A. and LEVY, S. L., "Application of Digital Simulation Techniques to Highway Design Problems." *Proc.,* Western Joint Computer Conf. May 1961.

5.29 HELLY, W., "Dynamics of Single-Lane Vehicular Traffic Flow." *Research Report No. 2,* Oct. 1959, Center for Operations Research, Massachusetts Institute of Technology.

5.30 HELLY, W., "Simulation of Bottlenecks in Single-Lane Traffic Flow." *Proc.,* Theory of Traffic Flow Symposium, 1961, pp. 207-238.

5.31 PERCHONOK, P. A. and LEVY, S. L., "Application of Digital Simulation Techniques to Freeway On-Ramp Traffic Operations." *Proc.,* Highway Research Board, Vol. 39, pp. 506-523 (1960).

5.32 WALTON, J. R., and DOUGLAS, R A., "A LaGrangian Approach to Traffic Simulation on Digital Computers." *Bull. 356,* Highway Research Board, 1962, pp. 48-50.

C. Traffic Assignment Models

5.33 CHARNES, A. and COOPER, W. W., "Extremal Principles for Simulating Traffic Flows in a Network." *Proc.,* National Academy of Sciences, Vol. 44, No. 2, pp. 201-204 (1958).

5.34 CHARNES, A. and COOPER, W. W., "Theories of Traffic Network." *Proc.,* Symposium on Theory of Traffic Flow, 1959, pp. 85-96.

5.35 HOFFMAN, W. and PAVELY, R., "Method for Solution of the Nth Best Path." *Jour., Association for Computing Machinery,* Vol. 6, No. 4, pp. 506-514 (Oct. 1959).

5.36 IRWIN, A., DODD, N. and VON CUBE, H. G., "Capacity Restraint in Assignment Programs." *Bull. 297,* Highway Research Board, 1961, pp. 109-127.

5.37 MOORE, E. F., "The Shortest Path Through a Maze." *Proc.,* International Symposium on Theory of Switching (April 1957), Harvard University Press, Part 2, pp. 285-292 (1959).

5.38 PANDIT, S. M. N., "The Shortest Route Problem—An Addendum." *Operations Research Jour.,* Vol. 9, No. 1, pp. 129-132 (Jan.-Feb. 1961).

5.39 PINNELL, C. and SATTERLY, G. T., JR., "System Analysis Technique for the Evaluation of Arterial Street Operation." Presented at Annual Meeting and Transportation Engineering Conf., American Society of Civil Engineers, 1962, 35 pp.

This technique applies the linear programming to the characterization of the traffic distribution on a street network.

5.40 POLLACK, M., "The Maximum Capacity Route Through a Network." *Operations Research Jour.,* Vol. 8, No. 5, pp. 733-736 (Sept.-Oct. 1960).

5.41 SMOCK, R. B., "A Comparative Description of a Capacity Restrained Traffic Assignment." *Record No. 6,* Highway Research Board, 1963, pp. 12-40.

5.42 WARDROP, J. G., "The Distribution of Traffic on a Road System." *Proc.,* Symposium on Theory of Traffic Flow, 1959, pp. 57-78.

5.43 WHITING, P. D. and HILLIER, J. A., "A Method for Finding the Shortest Route Through a Road Network." *Operational Research Quarterly,* Vol. 11, No. 1-2, pp. 37-40 (Mar.-June 1960).

D. General

5.44 BECKMAN, M., MCGUIRE, C. B. and WINSTEN, C. B., "Studies in the Economics of Transportation." 1956, Yale University Press.

5.45 BLANCHE, E., "Applying New Electronic Computers to Traffic and Highway Problems." *Traffic Quarterly,* Vol. XI, No. 3, pp. 406-416 (July 1957).

5.46 BRAIN, R., "Traffic Simulation for Urban Areas." *Traffic Engineering & Control,* Vol. 3, No. 9, pp. 534-537 (Jan. 1962).

An elementary introduction of the theory of traffic simulation is covered relative to prediction of traffic flows arising at some future date. Where alternative routes are available, the shortest or quickest route should be taken to establish the overall flow influence coefficient. An assignment curve for alternative routes was plotted. It was stated that the curve represents a potentially practical means of estimating flows in lesser urban areas.

5.47 BRAUNSTEIN, M. L., LAUGHERY, K. R. and SIEGFRIED, J. B., "Computer Simulation of Driver Behavior During Car Following: A Methodological Study." *Final Report,* Oct. 1962, prepared for the Bureau of Public Roads by Cornell Aeronautical Laboratory, 55 pp.

The applicability of complex information processing

computer modes to the study of driver behavior was explored in a series of experimental and analytical studies. Verbal reports and objective performance measures were collected during controlled observations of car following on a four-lane, limited-access highway. A model of the observed behavior was formulated in flow chart form. The parameters of the model were examined and one (threshold for a lead-car velocity change) was subjected to experimental study. It was concluded that computer modeling is a feasible and useful approach to the study of driver behavior.

5.48 CRAWFORD, A., "Three Experiments with Different Degrees of Simulation of the Road Situation." *Research No. RN 3593,* 1959, Road Research Laboratory.

5.49 "Digital Simulation of the Car-Following Situation." *Report No. 201-1,* July 1959, Study of Electronic Devices as Traffic Aids, Engineering Experiment Station, Ohio State University, pp. 7-27.

5.50 GERLOUGH, D. L., "Automatic Computers for Traffic Control." *Reprint No. 16,* Inst. of Transportation and Traffic Engineering, University of California.

5.51 GERLOUGH, D. L., "Analogs and Simulators for the Study of Traffic Problems." *Proc.,* California Street and Highway Conf., 1954, pp. 82-83.

5.52 GERLOUGH, D. L., and MATHEWSON, J., "Approaches to Operational Problems in Street and Highway Traffic." *Operations Research Jour.,* Vol. 4, No. 1, pp. 32-41 (Jan.-Feb. 1956).

5.53 GERLOUGH, D. L., "Control of Automobile Traffic; A Problem in Real Time Computation." *Proc.,* Eastern Joint Computer Conf., Dec. 1957, Washington, D.C., pp. 75-79.

5.54 GERLOUGH, D. L., "A Comparison of Techniques for Simulating the Flow of Discrete Objects." Presented at National Simulation Conf., Dallas, Tex., Oct. 1958.

5.55 GERLOUGH, D. L., "Traffic Inputs for Simulation on a Digital Computer." *Proc.,* Highway Research Board, Vol. 38, pp. 480-492 (1959).

5.56 GOODE, H. H., "Course Notes on Simulation and Theory of Traffic Flow." Inst. of Transportation and Traffic Engineering, University of California, Los Angeles.

5.57 GOODE, H. H., "Simulation—Its Place in System Design." *Proc.,* Inst. of Radio Engineers, Vol. 39, No. 12, pp. 1501-1506 (Dec. 1951).

5.58 GOODE, H. H., "The Application of a High-Speed Computer to Definition and Solution of the Vehicular Traffic Problem." *Operations Research Jour.,* Vol. 5, No. 6, pp. 775-793 (Nov.-Dec. 1957).

5.59 HAIGHT, F. A., WHISLER, B. F. and MOSHER, W. W., JR., "New Statistical Method for Describing Highway Distribution of Cars." *Proc.,* Highway Research Board, Vol. 40, pp. 557-564 (1961).

5.60 HARLEY, J., "Simulation Techniques in Operations Research." *Operations Research Jour.,* Vol. 6, No. 3 (May-June 1958).

5.61 HILLIER, J. A., WHITING, P. D. and WARDROP, J. G., "The Automatic Delay Computer." *Research Note RN/2291/JAH, PKW, JGW,* Aug. 1954, Unpubl., Road Research Laboratory.

5.62 HOFFMAN, W. and PAVELY, R., "Applications of Digital Computer to Problems in the Study of Vehicular Traffic." *Proc.,* Western Joint Computer Conf., 1958, pp. 159-161.

5.63 LEWIS, E., "A Digital Model for Vehicular Traffic." *Proc.,* Symposium on Digital Simulation Techniques for Predicting the Performance of Large-Scale Systems, University of Michigan, 1960, pp. 287-293.

5.64 MATHEWSON, J. H., TRAUTMAN, D. L. and GERLOUGH, D. L., "Study of Traffic Flow by Simulation." *Proc.,* Highway Research Board, Vol. 34, pp. 522-530 (1955).

5.65 NAAR, J., "Simulation of Vehicular Flow." M. S. Thesis, 1958, Massachusetts Institute of Technology.

5.66 SAAL, C. C., "Simulation of Highway Traffic by Computer." Bureau of Public Roads. (mimeo.)

5.67 TRAUTMAN, D. L., DAVIS, H. E., HEILFON, J., ER CHUN HO and ROSENBLOOM, A., "Analysis and Simulation of Vehicular Traffic Flow." *Research Report 20,* 1954, Inst. of Transportation and Traffic Engineering, University of California, Los Angeles.

5.68 TURNER, W. O., "Traffic Simulation." *Bell Laboratories Record,* Vol. 41, No. 9, pp. 346-350 (Oct. 1963).

5.69 WARE, W. H., "Digital Computers in Traffic Flow Problems." The Rand Corporation, 26 pp.

5.70 WOHL, M., "Simulations in Traffic Engineering." *Research Report No. 34,* Aug. 1960, Joint Research Project, Massachusetts Institute of Technology and the Massachusetts Dept. of Public Works.

5.71 WOHL, M., "Simulation—Its Application to Traffic Engineering." *Traffic Engineering,* Part I, Vol. 30, No. 11, pp. 13-17 (Aug. 1960); Part II, Vol. 31, No. 1, pp. 19-25 (Oct. 1960).

5.72 WONG, S. Y., "Traffic Simulation with a Digital Computer." *Proc.,* Western Joint Computer Conf., 1956, pp. 92-94.

Describes the general approach to simulation of traffic flow on a digital computer. A crude model of flow along a length of roadway is developed as an example. The results of simulation are reported.

5.73 WORRALL, R. D., "Simulation of Traffic Behavior on a Digital Computer." *Traffic Engineering & Control,* Vol. 5, No. 2, pp. 86-90, 94 (June 1963).

VI. STUDY METHODS AND EQUIPMENT

A. Equipment

6.01 BAKER, J., "Radar Measures Vehicle Speeds." *Traffic Quarterly,* Vol. 3, No. 3, pp. 239-50 (July 1949).

6.02 COX, N. T., "The Simultaneous Recording of Data in Experiments Using Several Moving Vehicles." *Research No. RN/3594,* 1959, Road Research Laboratory, 9 pp.

6.03 "Electronic Device 'Snoops' on Driver-Vehicle Performance." *Traffic Safety,* Vol. 57, No. 12, p. 18 (June 1963).

6.04 HULBERT, S., "The Driving Simulator." *Proc.*, California Street and Highway Conf., 1961, pp. 59-61.

6.05 MAY, A. D., JR. and KANEKO, E. T., "A Comparative Study of Two Vehicle Operating Characteristics Instruments." *Proc.*, Highway Research Board, Vol. 37, pp. 375-395 (1958).

6.06 MUELLER, E. A., "Recent Speed and Delay Instruments." *Traffic Engineering*, Vol. 25, No. 3, pp. 100-103 (Dec. 1954).

6.07 PLATT, F. N., "A New Method of Measuring the Effects of Continued Driving Performance." *Record No. 25*, Highway Research Board, 1963, pp. 33-57.

6.08 STACK, H. J., "A Survey of the Uses of Radar in Speed Control Activities." *Traffic Quarterly*, Vol. 8, No. 4, pp. 433-447 (Oct. 1954).

6.09 VAN TIL, C. J., "A New Camera-Intervalometer for Taking Spaced Serial Photos." *Research Report No. 17*, 1954, Inst. of Transportation and Traffic Engineering, University of California.

6.10 "Vehicle Speed and Headway Data by Simplex Producto Graph 1956, 1957, 1958, 1959." Port of New York Authority, Project and Planning Div., unpubl.

B. Field Methods

6.11 BERRY, D. S. and DAVIS, H. E., "A Summary of Development and Research in Traffic Signs, Signals and Markings." Presented at California Traffic Safety Conf., 1953, Inst. of Transportation and Traffic Engineering.

6.12 BERRY, D. S., "Field Measurement of Delay at Signalized Intersections." *Proc.*, Highway Research Board, Vol. 35, pp. 505-522 (1956).

6.13 BERRY, D. S., ROSS, G. L. D. and PFEFER, R. C., "Study of Left-Hand Exit Ramps on Freeways." *Record No. 21*, 1963, Highway Research Board, pp. 1-47.

6.14 CHARLESWORTH, G., "Methods of Making Traffic Surveys, Especially 'Before and After' Studies." *Research No. RN/1308*, Road Research Laboratory, 7 pp.

6.15 CONDER, L., "Means of Evaluating Intersection Improvement." *Abstracts*, Highway Research Board, Vol. 18, No. 3, pp. 15-22 (Mar. 1948).

6.16 GREENSHIELDS, B. D., "The Photographic Method of Studying Traffic Behavior." *Proc.*, Highway Research Board, Vol. 13, Pt. I, pp. 382-396 (1933).

6.17 GREENSHIELDS, B. D., "Some Time-Space Relationships of Traffic in Urban Areas." *Proc.*, Inst. of Traffic Engineers, 1946, pp. 114-134.

6.18 GREENSHIELDS, B. D., "Driving Behavior and Related Problems." *Record No. 25*, Highway Research Board, 1963, pp. 14-32.

A study was carried out on driver behavior based on the hypothesis that different classes of drivers exhibit different driving characteristics which may be measured and related to the driving environment. A "drivometer" (electronic recording device) was used to measure (a) driver actions, (b) vehicle motions, and (c) traffic events. A photographic technique for determining the latter was compared with results from the drivometer, with close correlation. An events index was defined to relate time rate of occurrence to driver actions. A multivariate analysis was carried out in a preliminary manner with fairly good results.

6.19 HIGGINS, H. C. and DUNN, R. E., "Urban Highway Route Evaluation." *Proc.*, Highway Research Board, Vol. 31, pp. 425-429 (1952).

6.20 HOMBURGER, W. S., "The Behavior of Drivers at Uncontrolled Intersections." *Traffic Engineering*, Vol. 22, No. 3, pp. 105-108 (Dec. 1951).

A study of an uncontrolled intersection was conducted in an urban area in California using photographic methods. The results showed that the conformance of drivers to the expected behavior approaching an uncontrolled intersection varied from 100% close to the point of conflict to about 50% at a distance of 100 feet. This trend was definitely established for preceding cars, and it was expected to be found for yielding cars if unbiased data could be obtained. The rule of right-of-way in effect in California had a significant effect on the behavior of drivers.

6.21 HOPKINS, R. C., "Vehicle Detection of Traffic Analysis and Control." *Traffic Engineering*, Vol. 31, No. 10, pp. 14-16 (July 1961).

6.22 "Intersection Study for Traffic Control." Michigan State Highway Dept.

6.23 JOHNSON, A. N., "Maryland Aerial Survey of Highway Traffic Between Baltimore and Washington." *Proc.*, Highway Research Board, Vol. 8, pp. 106-115 (1928).

6.24 LAUER, A. R., "Psychological Factors in Effective Traffic Control Services." *Traffic Quarterly*, Vol. 5, No. 1, pp. 85-95 (Jan. 1951).

6.25 "Manual of Traffic Engineering Studies." 1953, Accident Prevention Dept., Association of Casualty and Surety Companies, New York City, 278 pp.

6.26 PETROFF, B. B. and KANCLER, A. D., "Urban Traffic Volume Patterns in Tennessee." *Proc.*, Highway Research Board, Vol. 37, pp. 418-433 (1958).

6.27 PINNELL, C. and SATTERLY, G. T., JR., "Systems Analysis Technique for the Evaluation of Arterial Street Operation." Presented at Annual Meeting and Transportation Engineering Conf., 1962, American Society of Civil Engineers.

6.28 PLATT, F. N., "A Proposed Index for the Level of Traffic Service." *Traffic Engineering*, Vol. 34, No. 2, pp. 21-26 (Nov. 1963).

6.29 SCHENLER, W. W. and MICHAEL, H. L., "Urban Intersection Evaluation Utilizing Average Delay per Vehicle." *Joint Highway Research Project No. 7*, Feb. 1962, Purdue University.

6.30 SICKLE, S. M., "Continuous Strip Photography—An Approach to Traffic Studies." *Traffic Engineering*, Vol. 29, No. 10, pp. 11, 12, 59 (July 1959).

6.31 "Symposium on Signs." *The Highway Magazine*, Vol. 45, pp. 104-106 (May 1954).

6.32 "Traffic Operation Studies." Bureau of Public Roads, Washington, D.C., 1954.

6.33 "Traffic Safety Research—A Unique Method of Measuring Road Traffic, Vehicle and Driver Characteristics." Presented before IV World Meeting, International Road Federation, Madrid, Spain, Oct. 1962.

6.34 WALLEN, M. A., "The Use of Motor Vehicle Citations in Traffic Engineering Analysis." *Traffic Engineering,* Vol. 20, No. 8, pp. 26-31 (Apr. 1960).

6.35 WORRALL, R. D., "Time-Lapse Cine Photography Aids Traffic Studies." *Traffic Engineering and Control,* Vol. 4, No. 8, pp. 444-451 (Dec. 1962).

C. Statistical Analysis

6.36 BOWKER, A. H. and LIEBERMAN, G. L., "Engineering Statistics." Prentice-Hall, 1959, 585 pp.

6.37 CROW, E. L., DAVIS, F. A. and MAXFIELD, N. W., "Statistics Manual." Dover, 1960, 288 pp.

6.38 DIXON, W. J. and MASSEY, F. J., JR., "Introduction to Statistical Analysis." McGraw-Hill, 1956.

6.39 FELLER, W., "An Introduction to Probability Theory and Its Application." John Wiley & Sons, Vol. 1 (1950).

6.40 FORBES, T. W., "Statistical Techniques in the Field of Traffic Engineering and Traffic Research." Second Berkeley Symposium on Mathematical Statistics and Probability, 1951.

6.41 FREUND, J. E., "Modern Elementary Statistics." Prentice-Hall, 1960, 413 pp.

6.42 FRY, T. C., "Probability and Its Engineering Uses." Van Nostrand, 1928.

6.43 GERLOUGH, D. L. and SCHUHL, A., "Poisson and Traffic." ENO Foundation for Highway Traffic Control, 1955, 75 pp.

6.44 GREENSHIELDS, B. D. and WEIDA, F. M., "Statistics with Applications to Highway Traffic Analyses." ENO Foundation for Highway Traffic Control, 1952, 238 pp.

6.45 HAIGHT, F. A, WHISLER, B. F., and MOSHER, W. W., JR., "New Statistical Method for Describing Highway Distribution of Cars." *Proc.,* Highway Research Board, Vol. 40, pp. 557-564 (1961).

6.46 HALD, A., "Statistical Theory with Engineering Applications." John Wiley & Sons (Canada) 1952.

6.47 KENDALL, M. G., "The Advance Theory of Statistics." Vol. 1, Griffin & Co., London, 1943.

6.48 RICHMOND, S. B., "Principles of Statistical Analysis." Ronald Press, 1957, 491 pp.

6.49 SCHWAR, J. and PUY-HUARTE, J., "Statistical Methods in Traffic Engineering." *Special Report No. 26,* Engineering Experiment Station, Ohio State University.

6.50 WHISLER, B. F., "A Study of Certain Probability Models Which Aid in Classification of Sequences of Events into Non-Random, Partially Random or Completely Random Categories." M.A. Thesis, 1960, American University, Washington, D.C.

VII. GENERAL TEXT

7.01 "A Policy on Arterial Highways in Urban Areas." 1957, American Association of State Highway Officials, 558 pp.

7.02 "A Policy on Geometric Design of Rural Highways." 1954, American Association of State Highway Officials, 655 pp.

7.03 "Automobile Facts and Figures." Automobile Manufacturers Association, Detroit, Mich., 1961, 72 pp.

7.04 "Future Highways and Urban Growth." Wilbur Smith and Associates, New Haven, Conn., Feb. 1961, 376 pp.

7.05 "Highway Capacity Manual." U.S. Bureau of Public Roads, Washington, D. C., 1950, 147 pp.

7.06 "Illinois Laws Relating to Motor Vehicles." 1961, 236 pp.

7.07 "Manual on Uniform Traffic Control Devices for Streets and Highways." U.S. Bureau of Public Roads, Washington, D. C., June 1961, 333 pp.

7.08 MATSON, T. M., SMITH, W. S. and HURD, F. W., "Traffic Engineering." 1955, McGraw-Hill, 647 pp.

7.09 "Model Traffic Ordinance for Municipalities; Supplementing the Uniform Vehicle Code for States." Revised 1962, National Committee on Uniform Traffic Laws and Ordinances, Washington, D. C., 62 pp.

7.10 "Traffic Engineering Handbook." Inst. of Traffic Engineers and National Conservation Bureau, 1941, Hammond, H. F. and Sorenson, L. J., co-editors, 285 pp.

7.11 "Traffic Engineering Handbook." Second Edition, 1950, Inst. of Traffic Engineers, Evans, H. K., editor, 514 pp.

7.12 "Traffic Engineering Practice." 1963, E. & F. N. Spon Ltd., edited by Davies, E. and Cassie, W. F., 325 pp.

7.13 "Traffic Regulations." 1958, City of Chicago, 86 pp.

7.14 "State of Illinois Manual of Uniform Traffic Control Devices for Streets and Highways." 1963, Dept. of Public Works and Buildings, Div. of Highways, Springfield, Ill., 220 pp.

7.15 "Uniform Vehicle Code—A Guide for State Motor Vehicle Laws." Revised 1962, National Committee on Uniform Traffic Laws and Ordinances, Washington, D. C., 210 pp.

7.16 "United Nations Conference on Road and Motor Transportation." Document 1950, VIII. 2, United Nations, New York, 1950.

VIII. ACCIDENTS

8.01 "A Comparison of Signalized Intersectional Accidents Before and After the Installation of Two-Phase Volume-Density Controller with Minor Movement Controllers for Left Turns." 1961, 4 1 unpublished, 4:20, Minnesota Dept. of Highways, Traffic Engineering Section.

8.02 "Before and After Accident Study of Combination Stop Sign and Alternating Flasher Units." *File Reference No. 33-T10-10,* 1956, 2 1 unpublished 3:23, Michigan Highway Dept., Planning and Traffic Division.

8.03 "Before and After Accident Study of Flasher Unit Installed at Four-Way Stop Changed to Two-Way Stop." *File Reference No. 65-T1-1,* 1956, 2 1 unpublished, 3:24, Michigan Highway Dept., Planning and Traffic Division.

8.04 "Before and After Accident Study of Stop Ahead and Oversize Stop Signs." *File Reference No. 76-T10-2,* 1959, 2 1 unpublished, 3:16, Michigan Highway Dept., Traffic Division.

8.05 "Before and After Accident Study of Stop and Stop Ahead Signs." *File Reference No. 27-T7-1,* 1959, 2 1 unpublished, 3:14, Michigan Highway Dept., Traffic Division.

8.06 BILLION, C. E., "Community Study of the Characteristics of Drivers and Driver Behavior Related to Accident Experience." *Bull. 172,* Highway Research Board, 1958, pp. 36-92.

8.07 BRITTENHAM, T. G., GLANCY, D. M. and KARRER, E. H., "A Method of Investigating Highway Traffic Accidents." *Bull. 161,* Highway Research Board, 1957, pp. 30-47.

8.08 DAVIES, W. W., "Road Accidents and Road Structures." *Nature,* Vol. 153, No. 3881, pp. 330-333 (Mar. 1944).

8.09 FIELDING, R. H. and YOUNG, T. E., "Analysis of Flow on an Urban Thorofare." *Bull. 107,* Highway Research Board, 1955, pp. 35-49.

8.10 FORBES, T. W., "Analysis of 'Near Accident' Reports." *Bull. 152,* Highway Research Board, Committee on Road User Characteristics, 1956, pp. 23-37.

8.11 GURNETT, G. B., "Stop Ahead Study—Antelope Valley." *Study No. I-59-08.3,* 3 1 unpublished, 3:20, Los Angeles County Road Dept., Traffic and Lighting Div.

8.12 GURNETT, G. B., "Effects of Using Stops on High Volume Master Plan Highway." *Study No. I-59-7.1,* 4 1 unpublished, 3:12, Los Angeles County Road Dept., Traffic and Lighting Div.

8.13 GURNETT, G. B., PETERSON, K. M. and WATSON, L., "Accident Rates at Master Plan Intersections by Control Types and Volumes." *Study No. I-59-02.1,* 5 1 unpublished, 3:21, Los Angeles County Road Dept., Traffic and Lighting Div.

8.14 HALSEY, M., "Traffic Accidents and Congestion." 1941, J. Wiley & Sons, 408 pp.

8.15 HIGHWAY RESEARCH BOARD, "Report of the Committee on Traffic Control and Protection at Urban and Rural School Zones." *Proc.,* Highway Research Board, Vol. 21, pp. 322-330 (1941).

8.16 INST. OF TRAFFIC ENGINEERS, "Rates of Accidents Frequency at Traffic Controlled Locations to Non-Controlled Locations." *Traffic Engineers Technical Notebook,* 1952, pp. C5-C7.

8.17 LYDDON, A. J., "Road Junction Design in Relation to Safety." *Roads and Road Construction,* Vol. 17, No. 198, p. 175 (June 1939).

8.18 MANNING, J. R., "Accidents at Controlled Junctions." *Research No. 2133,* Road Research Laboratory, 6 pp. (1954).

8.19 MARKS, H. and GURNETT, G. B., "Accident Rate Change Upon Signalization." *Study No. I-57-09,* 7 1, 1957, unpubl., 4:2, Los Angeles County Road Dept., Planning Div.

8.20 MATHEWSON, J. H. and BRENNER, R., "Indexes of Motor Vehicle Accident Likelihood." *Bull. 161,* Highway Research Board, 1957, pp. 1-8.

8.21 MCMONAGLE, J. C., "Relation of Traffic Signals to Intersection Accidents." *Bull. 74,* Highway Research Board, 1953, pp. 46-53.

8.22 "New Type Stop Sign Cuts Accidents." *Michigan Roads and Construction,* Vol. 55, No. 15, p. 6 (Apr. 1958).

8.23 "One Year Before and After Study at Yield Sign Location." Detroit Dept. of Streets and Traffic, 1958, 5 1 unpubl., 3:26.

8.24 "Right-of-Way Signs Reduce Accidents 30 Percent." *Oregon Motorist,* Vol. 34, No. 3, p. 1 (May 1954).

8.25 "Six Months Use of 'Yield Right-of-Way' Signs." *Traffic Engineering,* Vol. 28, No. 1, p. 42 (Oct. 1957).

8.26 "Stop Sign Below Light Cuts Accident Rate." *Engineering News-Record,* Vol. 160, No. 24, p. 65 (June 1958).

8.27 "Stop Sign Report No. 1 for Arlington Heights." Prepared for Public Safety Committee, Engineering Dept., Arlington Heights, Ill., Jan. 1964, 15 pp., tables, maps and appendices.

The objective is to provide for the most efficient and safest movement of traffic in Arlington Heights, Ill. Intersections in one quadrant of the city were studied with respect to the street classification; traffic volume; type of intersection; number, type and rate of accidents; sight distance deficiencies; existing traffic signs; and width of each street. The recommendations include (a) adoption and implementation of an arterial street plan; (b) elimination and relocation of stop signs; and (c) adoption of new suggested warrants for traffic control signs.

8.28 SYREK, D., "Accident Rates at Intersections." *Traffic Engineering,* Vol. 25, No. 8, p. 312 (May 1955).

8.29 "The Yield Sign." Prepared for Traffic Section, National Safety Congress and Exposition, Engineers Group Session, 1953, National Safety Council, 16 pp.

8.30 "Traffic Accident Experience, Before and After Installation of Four-Way Stop Control." Illinois Div. of Highways, Bur. of Traffic, Springfield, Ill., 1957, 5 1 unpubl. 3:22.

8.31 "Traffic Control and Roadway Elements." American Safety Foundation, 1963, 124 pp.

8.32 WENGER, D. M., "Accident Characteristics of Four-Way Stop Control versus Two-Way Stop Control." Study

Thesis, May 1958, Yale Bureau of Highway Traffic, Yale University.

8.33 "Where a Stop Sign Proved Better Than a Traffic Signal." *American City*, Vol. 66, No. 1, p. 13 (Jan. 1951).

IX. PSYCHOLOGICAL AND DRIVER BEHAVIOR

9.01 CLEVELAND, D. E., "Driver Tension and Rural Intersection Illumination." *Traffic Engineering*, Vol. 32, No. 1, pp. 11-16 (Oct. 1961).

Because illumination decreases intersectional accidents by providing improved visibility and warning of danger and increased confidence and comfort, a scientific study was made on rural intersections to discover the actual effects of improved illumination. The galvanic skin response (GSR) was used to test the physiological effects of improved illumination. The results were somewhat as expected in that under the improved lighting conditions only 80 percent of the responses encountered in unlighted conditions were recorded.

9.02 FORBES, T. W., "Some Factors Affecting Driver Efficiency at Night." *Bull. 255*, Highway Research Board, 1960, pp. 61-71.

9.03 FORBES, T. W., KATZ, M. S., CULLEN, J. W. and DETERLINE, W. A., "Sleep Deprivation Effects on Components of Driving Behavior." *Highway Research Abstracts*, Vol. 28, No. 1, pp. 21-26 (Jan. 1958).

9.04 FORBES, T. W., "Driver Characteristics and Highway Operation." *Traffic Engineering*, Vol. 24, No. 2 (Nov. 1953).

9.05 FORBES, T. W., "Psychological Applications to the New Field of Traffic Engineering." *Jour. of Applied Psychology*, Vol. XXV, No. 1, pp. 52-58 (Feb. 1941).

9.06 FORBES, T. W., "Human Factors in Highway Design, Operation and Safety Problems." *Human Factors*, Vol. 2, No. 1, pp. 1-8 (Feb. 1960).

9.07 FORBES, T. W., "Problems in Measurement of Electrodermal Phenomena—Choice of Method and Phenomena—Potentials, Impedance, Resistance." Presented at Symposium on "Problems in Measuring Electrodermal Phenomena," Annual Meeting, American Psychological Assoc., St. Louis, Mo., Sept. 1961.

Reviews various methods which have been used to measure galvanic skin response. The phenomenon is described briefly and the differences resulting from the various methods are discussed. A method is suggested whereby simultaneous measurement of several responses can be eliminated and one significant response separated out. Accordingly, four methods were listed, based on accuracy and other measurement needs.

9.08 HEIMBACH, C. L., "Effective Distance of Urban Highway Travel for Supermarket Shopping Trips." Ph.D Dissertation, June 1963, University of Michigan, 136 pp.

An investigation was made to determine the correlation of a number of driver actions and vehicle maneuvers, and trip frequency to shopping centers. Data were collected via an instrumented vehicle and a questionnaire. Results indicate that the combination of several driver actions and vehicle maneuvers into an "effective distance" will yield an index which has a better correlation with trip frequency than either time or distance alone.

9.09 HOLMES, E. H., "Application of Driver Behavior and Vehicle Performance Studies." *Proc.*, Highway Research Board, Vol. 20, pp. 408-414 (1941).

9.10 KERMIT, M. L. and HEIN, T. C., "Effect of Rumble Strip on Traffic Control and Driver Behavior." *Proc.*, Highway Research Board, Vol. 41, pp. 469-482 (1962).

Rumble strips were installed and studied at four different locations in Contra Costa County, Calif. The results showed reduction in accidents, stop-sign violation, and vehicle approach speed and deceleration rates. The audible and tactile stimuli produced by the strips gives a faster reaction time than visual stimuli produce. Economic justification is analyzed in terms of accident cost reduction. Strip designs for a variety of road conditions are shown.

9.11 LAUER, A. R., SUHR, V. W. and ALLGAIER, E., "Development of a Criterion for Driving Performance." *Bull. 172*, Highway Research Board, 1958, pp. 1-8.

A test was developed to measure various items of driver performance which were correlated with the Roger Laver scale of driver ability to determine which set of items could be combined in a regression equation to describe driver performance with reasonable accuracy.

9.12 LAUER, A. R., "The Psychology of Driving; Factors of Traffic Enforcement." Thomas, 1960.

9.13 LAUER, A. R., "Psychological Factors in Highway Traffic and Traffic Control." *Traffic Quarterly*, Vol. V, No. 1, pp. 86-95 (Jan. 1951).

9.14 MICHAELS, R. M., "Tension Responses of Drivers Generated on Urban Streets." *Bull. 271*, Highway Research Board, 1960, pp. 29-43.

An attempt to relate driver tension responses to those events in traffic which cause an overt change in speed or lateral location of a test vehicle. Galvanic skin response (GSR) was employed to measure tension. The first goal was to detect difference between two streets serving approximately the same traffic function. The studied events including the highest average tension on both routes are, in order of magnitude, as follows: (a) Conflicts induced by other vehicles in the traffic stream; (b) Traffic signals and in-stream pedestrians; (c) Moving vehicle events and parking; and (d) Marginal pedestrians and streetcar loading platforms. The driver on urban streets is faced with a high rate of decision making and the more complex the demands made on him by the traffic situation the greater is the tension. In general, the results indicate that GSR may be a promising means of describing driver behavior, but there are several statistical and methodological problems inherent in its use which restrict its operational utility at present.

9.15 MICHAELS, R. M., "Effect of Expressway Design on Driver Tension Responses." *Bull. 330*, Highway Research Board, 1962, pp. 16-25.

The study was an attempt to use the galvanic skin response (GSR) technique to differentiate among the

characteristics of four different expressway designs. The results indicated that GSR could be related to interferences under certain conditions. A theory of comfort and convenience, based on GSR rates, is discussed.

9.16 PLATT, F. N., "Driving Behavior and Traffic Accidents." Presented at 42nd Annual Meeting, Highway Research Board, 1963.

9.17 SMEED, R. J., "Some Factors Influencing the Road Behavior of Vehicle Drivers." *Operational Research Quarterly,* Vol. 3, No. 4, p. 60-67 (Dec. 1952).

X. TRAFFIC FLOW CHARACTERISTICS

A. Capacity

10.01 BAYLEY, J. M., "Intersection Capacity." *Traffic Engineering,* Vol. 29, No. 6, pp. 11-16, 24 (Mar. 1959).

Discusses certain trends that were apparent from data collected for intersection capacity studies in Australia, including pedestrian effects on turning movements, signal timing, and "pressurized" intersections.

10.02 BELLIS, W. R., "Traffic Report Before and After Improvements at Intersection of Routes 1 and 25." *Proc.,* Highway Research Board, Vol. 30, pp. 377-396 (1950).

10.03 BUCKLEY, J. P., "Application of Highway Capacity Research." *Trans.,* American Society of Civil Engineers, Vol. 117, p. 851 (1952).

10.04 FRENCH, A., "Capacities of One-Way and Two-Way Streets with Signals and with Stop Signs." *Public Roads,* Vol. 28, No. 12, pp. 255-265 (Feb. 1956); *Bull. 112,* Highway Research Board, 1956, pp. 16-32.

A comparison of capacities between traffic signals and stop-sign control at four intersections in Washington, D. C. The effect of one-way and two-way street operation on these capacities also was studied.

10.05 GREENSHIELDS, B. D., "A Study of Traffic Capacity." *Proc.,* Highway Research Board, Vol. 14, p. 468 (1934).

10.06 HALSEY, M., "Handling Traffic at Intersections." *Proc.,* Conf. on Highway Engineering, University of Michigan, 1934, pp. 37-45.

10.07 HORN, J. W. and BLUMENTHAL, R. C., "Pressurized Intersections." Bruce Campbell & Assoc., Dec. 1956.

Twenty-one approaches of eight intermediate "pressurized" intersections in the metropolitan area of Boston, Mass., were analyzed and compared with results presented in the 1950 *Highway Capacity Manual.* Some of the results of the study are as follows: (a) The average reported capacities are higher than expected; (b) The capacity of an approach increases in direct proportion to its increase in width; (c) The most efficient range of approach widths is 25 to 35 ft; (d) Right turns affect capacity less than manual outlines; (e) If left turns are 50 percent or more of the total approach, they operate as through traffic with little reduction effect; and (f) If volume of commercial vehicles is greater than 20 percent, they have a greater reduction effect than the manual states.

10.08 KOEFOED, K. V. M., "The Capacity of Urban Streets and Intersections." *Roads and Road Construction,* Mar. 1956.

10.09 MERTZ, W. L., "A Study of Traffic Characteristics in Suburban Residential Areas." *Public Roads,* Vol. 29, No. 9, p. 208 (Aug. 1957).

10.10 NORMANN, O. K., "Results of Highway Capacity Studies." *Public Roads,* Vol. 23, No. 8, pp. 57-81 (June 1942).

10.11 PAK POY, P. G., "The Redesign and Capacity of Urban Intersections." *International Road Safety and Traffic Review,* Vol. X, No. 4, pp. 27-39 (Autumn 1962).

10.12 PELEG, M., "Encounter of Vehicles at Intersections." *Bull. Research Council Israel,* Vol. 7, No. 1, pp. 55-60 (Apr. 1959).

10.13 WEBB, G. M. and MOSKOWITZ, K., "Intersection Capacity." *Traffic Engineering,* Vol. 26, No. 4 (Jan. 1956).

B. Travel Time and Delay

10.14 BERRY, D. S., "Evaluation of Techniques for Determining Over-All Travel Time." *Proc.,* Highway Research Board, Vol. 31, pp. 429-440 (1952).

The studies deal with methods for field measurement of intersection delay and the effects of different signal timing plans on stopped-time delay during daylight hours at signalized intersection in the San Francisco Bay area. Three methods of measuring stopped-time delay are compared: (a) the ITTE delay meter, which accumulates vehicle-seconds of stopped-time; (b) a sampling method for estimating vehicle-seconds of stopped time; and (c) use of spaced serial photos to obtain both stopped time and travel time for each vehicle. The methods were found to be satisfactory for obtaining stopped-time delay at signalized intersections while some conclusions were arrived at concerning timing and delay.

10.15 BONE, A. J. and MEMMOTT, F. W., "Travel." Presented at 41st Annual Meeting, Highway Research Board, 1962, 37 pp.

10.16 COLEMAN, R. R., "A Study of Urban Travel Times in Pennsylvania Cities." *Bull. 303,* Highway Research Board, 1961, pp. 62-75.

10.17 GUERIN, N. S., "Travel Time Relationships." M. S. Thesis, 1958, Yale University.

10.18 HALL, E. M. and GEORGE, S., JR., "Travel Time: An Effective Measure of Congestion and Level of Service." *Proc.,* Highway Research Board, Vol. 38, pp. 511-529 (1959).

10.19 "Procedure Manual 3B—Determining Travel Time." National Committee on Urban Transportation, Public Administration Service, Chicago, 1958, 24 pp.

10.20 SAWHILL, R. B., "Travel-Time Techniques on a Two-Lane Rural Highway." *Student Research Report No. 3,* Jan. 1952, Inst. of Transportation and Traffic Engineering, University of California, Berkeley, 55 pp.

10.21 "Speeds and Travel Time Measurement in Urban Areas." Highway Research Board, Committee on Operating Speeds in Urban Areas, Jan. 1955, 46 pp. (mimeo.)

10.22 SOLOMON, D., "Accuracy of the Volume-Density Method of Measuring Travel Time." *Traffic Engineering,* Vol. 27, No. 6, pp. 261-262, 288 (Mar. 1957).

10.23 TANNER, J. C., "A Theoretical Analysis of Delays at an Uncontrolled Intersection." *Biometrika,* Vol. 49, No. 1-2, pp. 163-170 (1962).

10.24 VOLK, W. N., "Effect of Type of Control on Intersection Delay." *Proc.,* Highway Research Board, Vol. 35, pp. 523-533 (1956).

A study of stopped-time delay was undertaken in an attempt to provide data to support warrants for certain types of traffic control devices. A simple method of recording this delay was used. Under the moderate traffic volume conditions observed, the average delay to all vehicles required to stop was less at two-way stops and greatest at fixed-time signals. Also, it appears that with two-way stop control, stopped-time delay on a minor highway would increase with increasing volume of traffic on the major highway; but the data available did not permit determination of the degree of relationship.

10.25 WALKER, W. P., "Speed and Travel Time Measurements in Urban Areas." *Bull. 156,* Highway Research Board, 1957, pp. 27-44.

C. Speed

10.26 BERRY, D. S. and GREEN, F. H., "Techniques for Measuring Over-All Speeds in Urban Areas." *Proc.,* Highway Research Board, Vol. 29, pp. 311-318 (1949).

10.27 BERRY, D. S., "Distribution of Vehicle Speed and Travel Times." *Proc.,* Symposium on Mathematical Statistics and Probability, 1951, Berkeley, pp. 589-602.

10.28 BUNTE, W. F., "Methods for Evaluating Highway Features Which Influence Vehicular Speeds." *Illinois Cooperative Research Project 1HR-53,* Vehicular Speed Regulation, University of Illinois.

10.29 CROWTHER, R. F. and SHUMATE, R. P., "Sampling Design for Fixed-Point Speed Measurements." Traffic Institute Northwestern University, and Field Service Div., International Association of Chiefs of Police, 1960.

10.30 FROST, R. E., "Some Factors Affecting Traffic Speeds." *Joint Highway Research Report,* Purdue University, unpubl., 1942.

10.31 HAMMOND, H. F., "Report to Committee on Safe Approach Speeds at Intersections." *Proc.,* Highway Research Board, Vol. 20, pp. 653-666 (1940).

10.32 KEEFER, L. E., "The Relation Between Speed and Volume on Urban Streets." Quality of Urban Traffic Service Committee Report, Presented at 37th Annual Meeting, Highway Research Board, 1958.

10.33 "Moving Vehicle Method of Estimating Traffic Volume and Speeds." Cook County, Illinois Highway Dept., Chicago, 1956, 31 pp.

10.34 OPPENLANDER, J. C., "Multivariate Analysis of Vehicular Speeds." *Illinois Cooperative Research Project 1HR-53,* Vehicular Speed Regulation, Apr. 1962, Dept. of Civil Engineering, University of Illinois.

10.35 OPPENLANDER, J. C., BUNTE, W. F. and KADAKIA, P. L., "Sample Size Requirements for Vehicular Speed Studies." *Bull. 281,* Highway Research Board, 1961, pp. 68-86.

10.36 ROWAN, N. J. and KEESE, C. J., "A Study of Factors Influencing Traffic Speeds." *Research Project No. 17,* Texas Transportation Inst., Texas Highway Dept., Sept. 1961, 63 pp.

D. Traffic Flow

10.37 ADAMS, W. F., "Road Traffic and Probability." *Research No. RN/1109,* Road Research Laboratory, 1948, 39 pp.

10.38 "Alteration of Minor Traffic Flow Through Control Measures." *Proc.,* Inst. of Traffic Engineers, 1962, pp. 132-136.

10.39 BECKWITH, D. A., "On the Controlled Flow of Vehicular Traffic." Div. of Applied Mathematics, Brown University, 1956.

10.40 CHANDLER, R. E., HERMAN, R. and MONTROLL, E. W., "Traffic Dynamics: Studies in Car Following." *Operations Research,* Vol. 6, No. 2, pp. 165-184 (Mar.-Apr. 1958).

10.41 CLIFFORD, E. J., "The Measurement of Traffic Flow." *Traffic Engineering,* Vol. 26, No. 6, pp. 243-246, 256 (Mar. 1956).

10.42 FORBES, T. W., "Human Factor Considerations in Traffic Flow Theory." *Record No. 15,* Highway Research Board, 1963, pp. 60-66.

Presents certain mathematical relationships developed from previous experimental studies of traffic flow. An attempt is made to explain discontinuities in certain data on the basis of human factor variables. In particular, the volume-speed-density relationship is shown to be controlled by reaction times when flow density becomes so great as to have significant vehicular interaction.

10.43 GERLOUGH, D. L. and MATHEWSON, J. H., "Approaches to Operational Problems in Street and Highway Traffic." *Operations Research,* Vol. 4, No. 1, pp. 32-41 (Jan.-Feb. 1956).

10.44 GREENBERG, H., "An Analysis of Traffic Flow." *Operations Research,* Vol. 7, pp. 79-85 (1959).

10.45 GREENSHIELDS, B. D., "Quality of Traffic Transmission." *Proc.,* Highway Research Board, Vol. 34, pp. 508-522 (1955).

10.46 GREENSHIELDS, B. D., "The Quality of Traffic Flow." Quality and Theory of Traffic Flow, Bureau of Highway Traffic, Yale University, 1957, pp. 3-40.

One of the major objectives was to substitute measurement for opinion on characterizing the quality of traffic flow. Two applications of the quality index were included in the report: (a) the use of the index in the development of relative cost factors of vehicle operation as a method of expressing the efficiency of an urban street, and (b) a test of the correlation between gasoline consumption and traffic flow quality. Although more study and data are needed to develop more exact index measurements, the following con-

clusions should be pointed out: (a) quality numbers probably follow a ratio or logarithmic scale, or one in which equal increments along the scale have unequal significance, and (b) the quality of traffic flow has a better correlation with traffic density than traffic volume.

10.47 GREENSHIELDS, B. D., "Traffic Accidents and the Quality of Traffic Flow." *Bull. 208,* Highway Research Board, 1959, pp. 1-15.

An attempt was made to find if there is a correlation between quality of traffic flow and frequency of highway accidents. Three sections of highway with different accident frequencies per million vehicle-miles were selected for investigation. Two of the sections were two-lane and the third was three-lane. A traffic camera and a recording speedometer were used to collect data. The findings indicate that the flow index does not have the same correspondence with accident frequency on a three-lane road as on a two-lane road. It became clear during the study that the change of direction should be taken into account in the quality index. A study of the data indicates no clear cut correlation in all cases. But if low quality coincides with high frequency of accidents, quality may be used to anticipate highway mishaps.

10.48 GREENSHIELDS, B. D., "The Density Factor in Traffic Flow." *Traffic Engineering,* Vol. 30, No. 6, pp. 26-28, 30 (Mar. 1960).

10.49 HAIGHT, F. A., "Mathematical Theories of Road Traffic." *Special Report,* Inst. of Transportation and Traffic Engineering, Los Angeles, California, Mar. 1960, 42 pp.

10.50 HAIGHT, F. A., "Mathematical Theories of Traffic Flow." 1963, Academic Press, 242 pp.

10.51 HELLEY, W., "Dynamics of Single Lane Vehicular Flow." *Research Report No. 2,* Massachusetts Institute of Technology, Center for Operations Research, 1959, 145 pp.

10.52 HOLMES, E. H., "Effect of Control Methods on Traffic Flow at 17th and Constitution in Washington, D. C." *Proc.,* Highway Research Board, Vol. 13, pp. 400-402 (1933).

10.53 KELL, J. H., "A Theory of Traffic Flow on Urban Streets." *Proc.,* Western Section Meeting, Inst. of Traffic Engineering, 1960.

10.54 MAJOR, N. G. and BUCKLEY, D. J., "Entry to a Traffic Stream." *Proc.,* Australian Road Research Board, Vol. 1, Part 1, pp. 206-228 (1962).

Reports the investigation of the process of entry to a traffic stream. The purpose is to determine the relative merits of single and multiple entry points. An expansion is derived, using queuing theory, for mean delay to entering vehicles. The equation agrees well with field data. The effect of entering vehicles on the traffic stream is also investigated.

10.55 MAY, A. D., JR. and WAGNER, F. A., JR., "A Summary of Quality and Fundamental Characteristics of Traffic Flow." Part of a Joint Research Project, Michigan State University, Michigan State Highway Dept., and U.S. Bureau of Public Roads.

10.56 MOSKOWITZ, K., "Waiting for a Gap in a Traffic Stream." *Proc.,* Highway Research Board, Vol. 33, pp. 385-394 (1954).

10.57 NORMANN, O. K., "Variation in Flow at Intersections as Related to Size of City, Type of Facility and Capacity Utilization." (mimeo).

10.58 OLIVER, R. M. and BISBEE, E. F., "Queuing for Gaps in Highway Flow Traffic Streams." *Reprint No. 103,* Inst. of Transportation and Traffic Engineering, University of California.

10.59 OLIVER, R. M., "A Traffic Counting Distribution." *Reprint No. 101,* Inst. of Transportation and Traffic Engineering, University of California.

10.60 OLIVER, R. M. and JEWELL, W. S., "The Distribution of Spread." *Research Report 20,* Inst. of Transportation and Traffic Engineering, University of California.

10.61 OLIVER, R. M., "Distribution of Gaps and Blocks in a Traffic Stream." *Reprint No. 111,* Inst. of Transportation and Traffic Engineering, University of California.

10.62 PIPES, L. A., "An Operational Analysis of Traffic Dynamics." *Jour. of Applied Physics,* Vol. 24, No. 3, pp. 274-281 (Mar. 1953).

10.63 ROBINSON, B., "What Birmingham Has Done to Improve Arterial Traffic Flow." *Street Engineering,* Vol. 4, No. 5, p. 27 (May 1959).

10.64 ROTHROCK, C. A. and KEEFER, L. E., "Measurement of Urban Traffic Congestion." *Bull. 156,* Highway Research Board, 1957, pp. 1-13.

Use is made of the measure of time-of-occupancy to describe the level of congestion and lost time. Three possible levels are suggested based on (a) a minimum volume above which there is an increase in travel time, (b) a volume corresponding to practical capacity, and (c) the peak-hour volume.

10.65 SMEED, R. J., "Traffic Flow." *Operational Research Quarterly,* Vol. 8, No. 3 (1957).

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